Modification of Summertime Arctic Cloud Characteristics between a Coastal and Inland Site

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ABSTRACT

Cloud characteristics at two sites on the North Slope of Alaska separated by ~100 km have been examined for the warmer months of 2001–03 using data collected from microwave radiometers, ceilometers, rotating shadowband radiometers, and pyranometers. Clouds at the inland site, Atqasuk, were found to have approximately 26% greater optical depths than those at the coastal site, Barrow, and the ratio of measured irradiance to clear-sky irradiance was nearly 20% larger at Barrow under cloudy conditions. It is hypothesized that a significant factor contributing to these differences is the upward fluxes of heat and water vapor over the wet tundra and lakes. Support for this hypothesis is found from the behavior of the liquid water paths for low clouds, which tend to be higher at Atqasuk than at Barrow for onshore winds but not for offshore ones, from differences in sensible heat fluxes, which are small but significant over the tundra but are nearly zero over the ocean adjacent to Barrow, and from the mixing ratios, which are significantly higher at Atqasuk than at Barrow. Results from a simple model further indicate that latent heat fluxes over the tundra and lakes can account for a significant fraction of the differences in the estimated boundary layer water content between Barrow and Atqasuk.

1. Introduction

The study of arctic clouds presents a range of problems not normally encountered in cloud studies for more temperate regions. Curry et al. (1996) provide a review of many of the relevant issues, including the absence of solar radiation for long periods, cloud-radiation feedbacks, cold and dry wintertime conditions, temperature inversions, etc. For the warmer months of the year many of these complications are less severe or absent, at least over coastal and inland regions. However, in contrast to lower latitudes, arctic cloudiness increases during the summer months, driven by the increased availability of moisture from higher surface evaporation (Vowinckel and Orvig 1970). During this period, the prevailing cloud types over the polar ocean and the adjacent coastal areas are stratus or stratocumulus (Warren et al. 1986, 1988). Farther inland the overall incidence of cloudiness decreases and the incidence of cumulus clouds becomes larger while that of stratus and stratocumulus decreases. As an example, the frequencies of stratus and stratocumulus over the ocean and in the coastal area near Barrow, Alaska, are given by Warren et al. (1986, 1988) as 69% and 66%, respectively, during the summer months. In the grid area adjacent to the coastal site the frequency drops to only 41%, and the frequency of cumulus clouds increases to 20% from a value of 4% at the coast. Similar trends are found over broad regions of the Arctic, including Alaska and Siberia. The mean base heights of the clouds also rise as one moves inland, although Warren et al. (1986) warn that the "base height of the lowest cloud is sometimes measured, but in most of the reports it is estimated subjectively." The spatial evolution in cloud properties is also accompanied by associated changes in the optical properties of the clouds. Vowinckel and Orvig (1970) comment that dynamic processes will favor clouds of greater depth as one moves south from the ocean, and the optical thickness of the clouds is therefore likely to increase.

Most detailed studies of arctic clouds have been done over the ocean or along coastal areas (e.g., Hobbs and Rangno 1998; Beesley and Moritz 1999; Kahl et al. 1999; Curry et al. 2000; Uttal et al. 2002; Tjernström et al. 2004) with comparatively less attention paid to in-

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land locations (e.g., Kahl et al. 1992; Gultepe et al. 2000). Vowinckel and Orvig (1970) described climatological features over the Arctic Basin and Greenland, and Warren et al. (1986, 1988) included statistics on cloud types and amount over both the Arctic Ocean and the land regions. Although not focusing on inland sites, Maxwell (1980, 1982) described the climate of Canadian arctic islands and adjacent waters. In-depth studies of the transformations of clouds from coastal to nearby inland areas remain scarce, however. For example, the Vowinckel and Orvig, Maxwell, and Warren studies were intended as broad descriptions of the climatology rather than detailed analyses of the underlying processes responsible for the results presented. Moreover, the Warren studies presented results at a resolution of no better than 5° × 5°, and the number of inland stations adjacent to arctic coastlines was limited in many areas. Contrasts between the surface energy balances over land and water surfaces (discussed later in this paper) are expected to contribute to the differences in cloud properties as one moves inland from coastal regions, at least during the warmer months when the land surfaces are snow free, and clearly can occur over scales significantly smaller than 5° × 5°. The characterization of clouds in these areas, the determination of the processes that account for the observed differences, the representation of those processes in models, and the accurate simulation of cloud physical and optical characteristics in coastal transition zones are challenging and important issues for climate studies and modeling.

To help address such issues, the U.S. Department of Energy's Atmospheric Radiation Measurement Program (ARM) has established two study sites in Alaska, one at Barrow on the coast and one at a site inland approximately 100 km to the southwest at Atqasuk; collectively, these are known as the North Slope of Alaska or NSA site (Fig. 1). Each site is equipped with a variety of radiometric and other instruments suitable for the study of cloud properties.

Using ARM data from May to September 2000, Dong and Mace (2003) did an extensive characterization of cloud properties at Barrow. They also made some comparisons of the cloud microphysical properties there with results from earlier studies over the Beaufort Sea and the Surface Heat Budget of the Arctic Ocean (SHEBA; Perovich et al. 1999) site, and concluded that the results from their analysis were broadly similar to results from previous arctic campaigns. They went on to assert that "The ARM NSA site seems to represent reasonably well Arctic land areas and adjacent open-ocean regions. . ." but they did not actually make use of any data from Atqasuk.

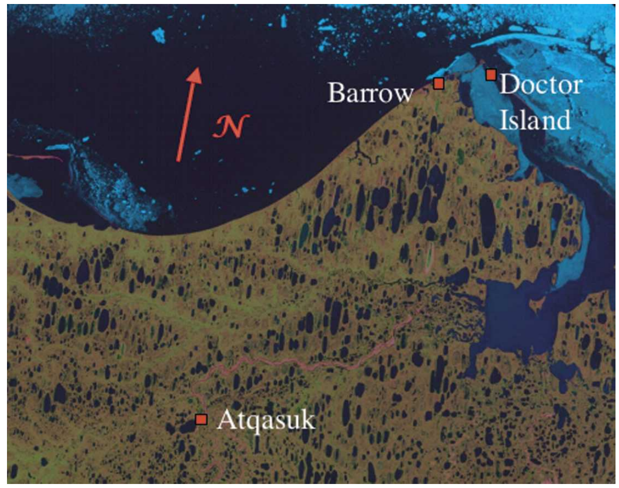

FIG. 1. Map of the North Slope of Alaska region showing the two ARM NSA sites, Barrow and Atqasuk, and the Doctor Island site used for heat flux measurements in 2000. The separation of Barrow and Atqasuk is approximately 100 km.

During the colder months of the year, when the oceans are frozen and the land surfaces are covered with snow, there is little reason to expect significant differences in cloud properties between coastal and adjacent inland regions, provided there are no large leads near the coast or major topographical relief farther inland. During the warmer months, when the snow cover over land has melted and the ice has retreated from the coastal areas, however, the situation is quite different. Under such conditions, the properties of low-level clouds may be affected by surface fluxes of sensible and latent heat, which will be different over the cold ocean and warmer land. Maxwell (1980) notes that convection is common over Canadian Arctic islands but also notes (Maxwell 1982) that the interior and lee sides of islands are more likely to be cloud free because of heating of the land. Surface fluxes were also suggested as possibly important in a study by Doran et al. (2002) in which liquid water paths (LWPs) at Barrow and Atqasuk were compared for June–September 1999.

Since 2000 there have been significant improvements in the instrumentation and data recovery at Barrow and Atqasuk. These factors, along with the availability of a longer data record, have allowed us to make a more extensive, robust, and detailed comparison of the cloud properties at Barrow and Atqasuk and to assess how well observations at Barrow can be used to characterize the cloud environment farther inland. In this paper we present some results from that comparison, describe a hypothesis for the mechanisms responsible for the observed differences in cloud properties at the two sites, and present some supporting evidence for that hypothesis.

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2. Instrumentation and data

a. Instruments

Although Barrow is more comprehensively equipped than Atqasuk, each site has a number of instruments in common, and the data from these common instruments are used in this study for comparing the cloud properties at the two locations. Each site has a microwave radiometer (MWR; Radiometrics Corporation) that measures brightness temperatures at 23.8 and 31.4 GHz, and LWPs are retrieved from the values measured at these two frequencies (e.g., Liljegren et al. 2001). A Vaisala CT25 ceilometer provides cloud-base values at heights up to 7.6 km with a vertical resolution of 15 m. A multifilter rotating shadowband radiometer (MFRSR) from Yankee Environmental Systems, Inc., measures the direct normal, diffuse horizontal, and total horizontal components of the broadband irradiances using a silicon detector, and these same components at six wavelengths (415, 500, 615, 673, 870, and 940 nm) with a nominal passband of 10 nm at each wavelength. An Eppley Precision Spectral Pyranometer (PSP) provides hemispherical downwelling solar irradiance in the 280–2950-nm range. In addition to the radiometric measurements, we have used mean wind, temperature, and humidity data collected at 2 m above the surface from two instrumented towers operated by the ARM Program.

During the summer of 2000, we collected data from a three-axis sonic anemometer (Applied Technologies, Inc.) on a small tower mounted on a grounded barge on Doctor Island. The island is situated just off the coast to the northeast of Barrow (Fig. 1), has an elevation of no more than 1 m MSL, is only about 50 m wide, and was surrounded by ice until the melt in mid-June. The anemometer, located about 15 m from the eastern shore of the island, sampled wind components and virtual temperature at a rate of 10 s^{-1}. The upwind fetch for virtually all directions was thus over water. Sensible and latent heat flux data are also available from FLUXNET (Baldocchi et al. 2001) sites at Barrow and Atqasuk that are operated by San Diego State University. Both sites sample winds and virtual temperature with a three-axis sonic anemometer (Gill Instruments, model R3) at a rate of 10 s^{-1}. Water vapor fluctuations are measured with an open-path H_2O/CO_2 sensor manufactured by National Oceanic and Atmospheric Administration (NOAA)'s Atmospheric Turbulence and Diffusion Division (Auble and Meyers 1992).

b. Data records and processing

For the radiometric and cloud measurements we used data from the warmer months (June–September) from three years, 2001–03, for our analysis. We were primarily interested in snow-free surface conditions so we further restricted our sampling to 15 June through 14 September of each year. For the three years this provided a total of 6624 possible hours of data.

There has been considerable discussion about the use of MWRs in arctic environments (Westwater et al. 2001; Lin et al. 2001). Uncertainties in the measured brightness temperatures and the spectroscopy for supercooled water in clouds can lead to large relative uncertainties in retrieved LWP values in the dry conditions prevailing in this region during the colder months. Fortunately, this problem is less serious during June–September when atmospheric moisture is considerably greater. Similarly, the uncertainties in spectroscopy are reduced during the summer because cloud temperatures, especially for low clouds, are generally higher.

The MWR collects data at 20–30-s intervals. For these analyses we averaged the data either to 5-min or 1-h values. We have used the empirical but physically based retrieval algorithms developed by Liljegren et al. (2001) to obtain the LWPs at both Barrow and Atqasuk. The Liljegren et al. algorithms make use of the surface temperature, pressure, and relative humidity to help extract LWP values from brightness temperatures. Their approach can also make use of cloud temperatures but these were not available at Atqasuk. Thus, in order to apply a consistent treatment to the data at both sites, we have only used surface temperature data. Liljegren et al. show that this is unlikely to cause serious uncertainties for clouds with LWPs below 250 g m^{-2}, which covers the large majority of the cases (see below).

A sensor on the MWR is supposed to determine when the Teflon window covering the instrument mirror has water on it and set a warning flag in the data stream, but there are indications that not all wet window conditions were flagged. In particular, anomalously high values of LWP were occasionally found. For this analysis, we have eliminated hourly averaged LWP values if they exceeded 500 g m^{-2}; only about 4% of the Barrow and Atqasuk values were eliminated by this cutoff value. Of the remaining values, 94% of the LWP values at Barrow had LWPs less than or equal to 250 g m^{-2} while at Atqasuk, 91% fell into this category. However, because averages can still be affected by a small number of outliers and because the distributions are highly skewed, we have chosen to use median values when characterizing the behavior of LWPs.

Cloud-base heights were recorded by ceilometers every 15 s. Clear-sky conditions were assigned an arbitrarily high cloud-base value, so for broken cloud con-

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ditions successive ceilometer readings can vary widely and mean values may be misleading. As a result, median values were tabulated for each hour instead. Up to three cloud-base heights could be discerned but only the lowest ones were used for this analysis. If a return signal indicated obscured conditions but a maximum in the backscattered light could still be determined, that maximum was used as the base height. For all other obscured conditions (such as might occur in fog) or if data were missing, no value was assigned. (We expect that a small number of cases with high, thin clouds were put into the clear-sky category and this reflects a basic limitation of the ceilometer. Other techniques can be used to try to identify such cases but would add little to our analysis and were not pursued.) An hour's median cloud-base height was calculated if at least 70% of the readings for that hour were accepted. Approximately 15% of the hours at Barrow and 12% of those at Atqasuk were eliminated because an insufficient number of valid scans was obtained for the hours in question and an additional 7% of the hours at each site were unavailable because of instrument malfunction or other problems. This resulted in an overall data recovery rate for the ceilometers of approximately 79% at Barrow and 81% at Atqasuk.

The PSPs obtained 1-min averages of downwelling hemispheric radiation. We were interested primarily in the difference in solar irradiances at Barrow and Atqasuk and how those differences might be related to cloud cover. Rather than averaging over all hours of a day, which would mask some of the differences when the sun is close to or below the horizon, we restricted our analysis to daytime hours.

Both broadband (PSP) data and the MFRSR data, along with LWP values from the MWR, were used to calculate cloud optical depths, τ_c, and cloud droplet effective radii, r_e, during periods when the cloud fraction was 0.95 or larger as determined from the method of Long et al. (1999). Irradiances from the MFRSR were collected at 20-s intervals, and the instrument was monitored for the stability of its calibration using the Langley method (Harrison et al. 1994). This monitoring was performed prior to, during, and after the instruments' deployment at the NSA sites. Because of this effort, we believe the measurements from the MFRSR are quite accurate and approach the 1% goal described by Michalsky et al. (2001). The data recovery from the MFRSR was about 95% or greater for each of the three years considered here.

Turbulent sensible heat fluxes at Doctor Island were calculated over half-hour intervals after subtracting linear trends of the temperature and vertical velocity. Fluxes of water vapor at the Ameriflux sites were also calculated over half-hour intervals in a manner similar to our approach. Precipitation and other interferences occasionally caused outliers in the Doctor Island data, and data from periods in which heat fluxes were less than -100 W m^{-2} or greater than 150 W m^{-2} were rejected. Approximately 8% of the data were eliminated by this filter.

3. Results

For the periods with valid ceilometer data, clear conditions were found 19% of the time at Barrow and 23% of the time at Atqasuk. For cloudy periods, the 25th percentile, median, and 75th percentile values of cloud-base heights at Barrow were 140, 270, and 710 m, respectively, whereas the corresponding figures for Atqasuk were 230, 450, and 1110 m. The median LWP at Barrow for all conditions for the warmer months of 2001–03 was 39 g m^{-2} while the median value at Atqasuk was 51 g m^{-2}, or 31% higher. If we select only those periods when the ceilometers indicated clouds, the difference in LWPs between the two sites was still larger, with median values of 59 and 81 g m^{-2} at Barrow and Atqasuk, respectively. Thus, although cloud-base heights at Atqasuk tended to be higher than at Barrow and clear conditions were more likely to be found there, the clouds that did occur at Atqasuk had higher liquid water paths than those at Barrow. Note that the LWP values are column-integrated quantities so that liquid clouds at any level can contribute to the total but, as shown later, the largest differences between the two sites were found for low-level clouds.

As expected for arctic summertime conditions, the cloudy periods were also persistent. Using 5 min as a basic averaging time over which to compute LWPs, we calculated the distribution of cloudy events, where an event is a sequence of 5-min periods with an LWP exceeding a threshold value used to define cloudy conditions. We further determined what percentage of the total time when the LWP exceeded the selected threshold was accounted for by longer events, for example, those persisting for an hour or more. For a threshold of 20 g m^{-2}, approximately 88% of the total cloudy time at Barrow and 90% of the total cloudy time at Atqasuk lasted for one or more hours. Even if the threshold is raised to 75 g m^{-2}, the corresponding values are 80% at both sites. These results are consistent with the presence of predominantly stratiform clouds for extended times at Barrow and Atqasuk.

Figure 2 shows the ratio of measured irradiance to clear-sky irradiance from the PSPs at Barrow and Atqasuk, for all cases and for cases with at least 95% cloud cover, as a function of the cosine of the solar zenith

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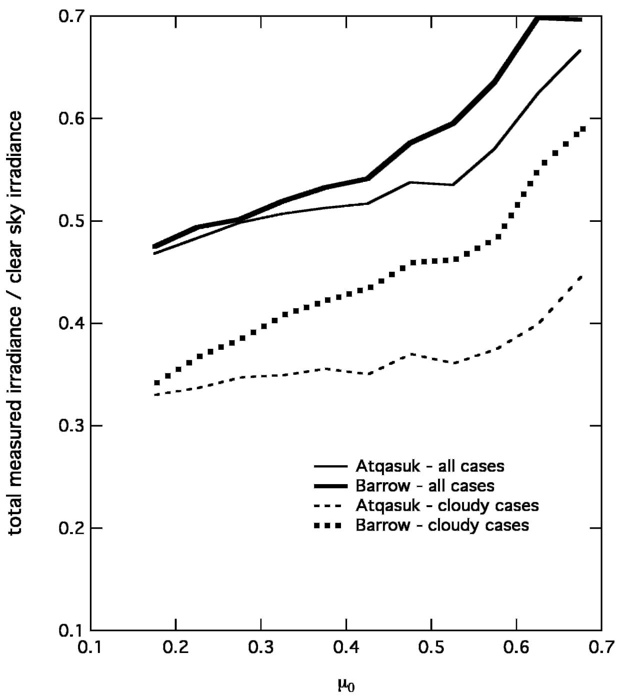

FIG. 2. Ratio of measured irradiance to clear-sky irradiance at Barrow and Atqasuk, for all conditions and for conditions with at least 95% cloud cover, as a function of the cosine of the solar zenith angle.

angle, μ_0. The clear-sky irradiance is the irradiance that a site would experience in the complete absence of clouds, as calculated using the method of Long and Ackerman (2000). The occurrence of 95% or more cloud cover was diagnosed using the approach of Long et al. (1999), who used data from a hemispherical sky imager to deduce a relationship between diffuse radiation and sky cover. The results are striking. For the "all cases" category, the ratios at Atqasuk are generally less than those at Barrow, with the difference increasing with decreasing zenith angle. The separation is even larger for cases when there is nearly complete overcast, indicating that there are important differences in the cloud properties between the two sites. For daytime hours when the ceilometers detected any clouds, the average irradiance at Barrow was about 19% larger than that at Atqasuk, with values of 165 and 139 W m^{-2}, respectively. Because of the difference in latitudes of the two sites, in the absence of clouds and assuming identical aerosol properties at the two sites, the irradiance at Barrow during daylight hours in the middle of the summer would be about 2% less than that at Atqasuk.

Cloud optical depths and cloud effective droplet radii were calculated separately with two algorithms that used as input either narrowband MFRSR data or broadband PSP data. The algorithms, as well as the input irradiance data fed to them, are independent of one another, and this independence provides a check on the reliability of the computed τ_c and r_e. The algorithm applied to the MFRSR data was developed by Min and Harrison (1996) and uses 415-nm MFRSR irradiances, LWPs (from the MWR), and surface albedo (at 415 nm) to find τ_c and r_e. The broadband code is based on the Santa Barbara discrete ordinate radiative transfer model (DISORT) Atmospheric Radiative Transfer (SBDART) model (Ricchiazzi et al. 1998) and is similar in spirit to other broadband codes (e.g., Boers 1997; Dong et al. 1997); it has been briefly described in Barnard et al. (2001). The input to the Barnard algorithm includes surface albedo, LWP, columnar water vapor, and surface broadband irradiances. Broadband albedos were determined using down-looking pyranometers mounted on 10-m towers coupled with measurements from up-looking pyranometers. The albedos of tundra and water bodies are nearly the same at 415 nm, so the point measurements of the albedos at Barrow and Atqasuk are assumed to be representative of the surface albedos integrated over the vicinity of the measurement locations.

Although the data required to apply these algorithms were usually available during the entire period of the arctic day, the algorithms were only used if two conditions were met. The first of these is that the cosine of the solar zenith angle must be greater than 0.15. Second, we only include results when the indicated cloud fractions were greater than or equal to 0.95 over a 5-min averaging period because the plane-parallel assumption that underpins the cloud optical thickness algorithms is most closely satisfied under these conditions.

Results from these two methods are shown in Table 1 (τ_c) and Table 2 (r_e) for the three years of our study. The results presented in these tables are medians of 5-min averages taken from times when it was possible to calculate optical thicknesses from both algorithms. The number of such coincident cases is listed in the last column of these tables. They amount to approximately 18% of the possible hours at Atqasuk and 19% of those at Barrow.

Differences between the two algorithms for both τ_c and r_e are of order 1 (dimensionless and μm, respectively). The Min–Harrison algorithm tends to calculate τ_c that are less than the corresponding broadband values, while the r_e from the Min–Harrison algorithm are greater; this behavior is consistent with the inverse relationship between τ_c and r_e for a fixed LWP. The table shows that the difference in τ_c between the sites—ranging from 2.4 to 5.1 optical depth units—is substantially larger than the difference between algorithms for

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TABLE 1. Median cloud optical thicknesses derived from the Min–Harrison and broadband algorithms.

Year	Site	Min–Harrison	Broadband	Difference (Min–Harrison–broadband)	Number of observations
2001	Atqasuk	16.7	18.0	−1.3	4627
2001	Barrow	14.3	15.6	−1.3	4659
2002	Atqasuk	17.7	17.6	0.1	4612
2002	Barrow	12.6	13.3	−0.7	4061
2003	Atqasuk	16.8	17.3	−0.5	4710
2003	Barrow	13.0	13.5	−0.5	6255

a given site and given year, thus demonstrating that when warm-season clouds are present at the two sites, τ_c is larger at Atqasuk than at Barrow. This conclusion applies whether one uses the narrowband or broadband calculations.

For each of the three warm seasons, the median broadband optical depths at Barrow were smaller than those at Atqasuk (Table 1). For the three seasons together the median, 25th, and 75th percentile values at Barrow were 14.1, 8.8, and 21.4, respectively, while the corresponding values at Atqasuk were 17.7, 11.5, and 26.2. The effective droplet radii show no consistent trend from year to year, and taken over the 3-yr study period the median and 25th and 75th percentile values at the two sites turn out to be the same: 9.1, 6.9, and 11.9 μm, respectively.

Dong and Mace (2003) reported higher values of effective radii at Barrow but a comparison of our results with theirs must be done with caution. Their analysis, for one year, included the month of May, early June, and late September, none of which is included in our analysis. Further, they reported mean values for effective radii, LWP, etc., whereas we prefer to use median values, which we think are better suited for describing highly skewed quantities. For r_e they found a mean value of 11.0 μm compared to a value from our data of 10.0 μm. Given the large spread about the mean values for both datasets, the results agree rather well. Similar agreement was found for quantities such as LWP and cloud-base height.

The differences in τ_c, and the similarities in r_e, that we found between the Barrow and Atqasuk sites are illustrated in plots of the normalized probability density functions (PDFs) for these two variables. These distributions are shown in Fig. 3 for the broadband calculations. Clearly, the cloud optical properties, in terms of cloud optical depths, are different, while the effective radii distributions are remarkably similar.

The difference in observed surface irradiances when clouds are present, discussed earlier, is consistent with the differences in median optical thicknesses between the sites. This can be demonstrated by using Eq. (4) of Barnard and Long (2004), which approximates the total surface broadband irradiance, D (for $\tau_c > 10$) by

$$D(\tau_c, g, \mu_0) = (\pi F_0)\frac{5{\mu_0}^{1.51}}{4 + 3(1 - A)(1 - g)\tau_c}, \qquad (1)$$

where μ_0 is the cosine of the solar zenith angle, A is the surface broadband albedo, g is the asymmetry parameter for cloud droplets, and πF_0 is the broadband solar forcing at the top of the atmosphere between wavelengths where cloud absorption is small (0.25 μm $< \lambda \leq 1$ μm). Forming the ratio, r, between the broadband irradiances at each site gives

TABLE 2. Median cloud effective radii (μm) derived from the Min–Harrison and broadband algorithms.

Year	Site	Min–Harrison	Broadband	Difference (Min–Harrison–Broadband)	Number of observations
2001	Atqasuk	10.7	9.4	1.3	4627
2001	Barrow	10.2	8.8	1.4	4659
2002	Atqasuk	9.6	9.1	0.5	4612
2002	Barrow	10.8	9.6	1.2	4061
2003	Atqasuk	9.5	8.7	0.8	4710
2003	Barrow	10	9.0	1.0	6255

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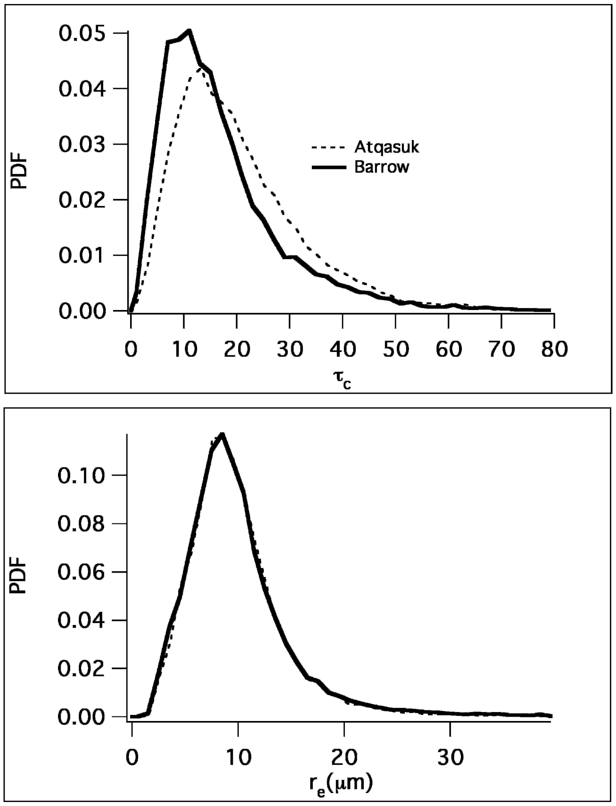

FIG. 3. Probability density functions for the distributions of τ_c and r_e.

$$\left(\frac{D_{\mathrm{BAR}}}{D_{\mathrm{ATQ}}}\right) = \left(\frac{\mu_{0,\mathrm{BAR}}^{1.51}}{\mu_{0,\mathrm{ATQ}}^{1.51}}\right) \times \left[\frac{4 + 3(1 - A_{\mathrm{ATQ}})(1 - g_{\mathrm{ATQ}})\tau_{c,\mathrm{ATQ}}}{4 + 3(1 - A_{\mathrm{BAR}})(1 - g_{\mathrm{BAR}})\tau_{c,\mathrm{BAR}}}\right], \qquad (2)$$

where the subscripts BAR and ATQ refer to Barrow and Atqasuk, respectively. To approximate the μ_0 ratio we take the values at solar noon for a date in the middle of the time period under consideration, 1 August. This gives $\mu_{0,\mathrm{BAR}} = 0.594$ and $\mu_{0,\mathrm{ATQ}} = 0.606$. Taking $A_{\mathrm{BAR}} = A_{\mathrm{ATQ}} = 0.16$, $g_{\mathrm{BAR}} = g_{\mathrm{ATQ}} = 0.87$, we then need values for τ_c at each site. We take these to be the median values derived from the Min algorithm, 17.0 and 13.3, for Atqasuk and Barrow, respectively. The broadband irradiance ratio calculated from (2) is 1.11. Given the approximations used in this calculation, the result is in reasonable agreement with the observed ratio of 1.19. Because the optical thicknesses derived from the Min–Harrison algorithm are independent of the surface broadband irradiances, the similarity between the calculated and observed ratios suggests that the derived optical thickness values and surface broadband irradiance measurements are consistent.

Sensible and latent heat flux data at Barrow and Atqasuk are not readily available for the time period (2001–03) considered in this study but we have been able to procure data for the years 1999–2001. The median sensible heat fluxes at Barrow and Atqasuk were similar, as were the latent heat fluxes. Figure 4 summarizes these results for all hours of the day and for 0900–1500 local standard time (LST), the time period when the fluxes would be expected to be largest. For the Doctor Island site, the only flux data available are sensible heat fluxes for the year 2000. This is not a serious issue because the 2000 sensible and latent heat flux values at Barrow and Atqasuk are seen to be representative for the longer period (1999–2001) as well. The differences between the fluxes at Doctor Island and those at Barrow and Atqasuk are striking. The Doctor Island median sensible heat flux, which characterizes the conditions over the cold water offshore from Barrow, was near zero for the summer of 2000, even for the

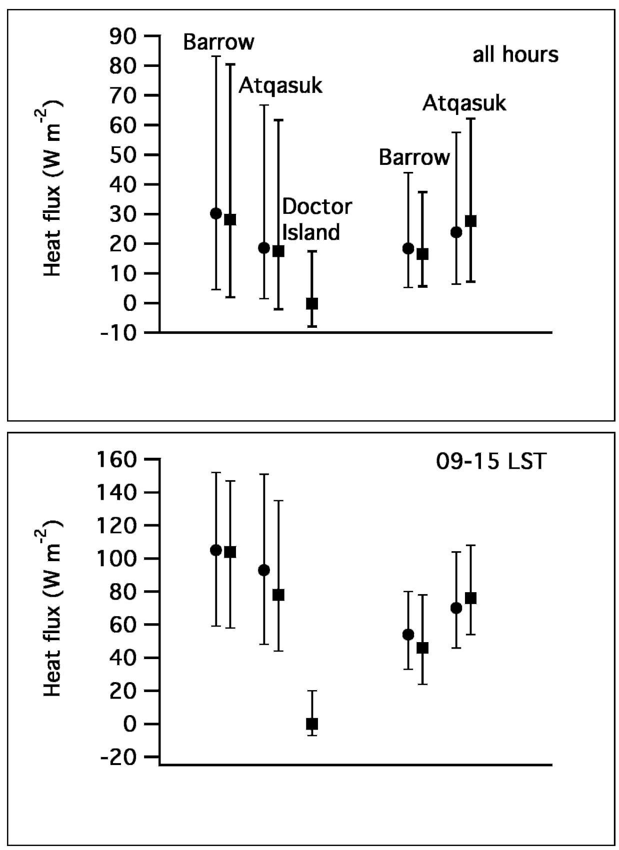

FIG. 4. (left) Sensible and (right) latent heat fluxes at Barrow, Atqasuk, and Doctor Island. Symbols denote median values and vertical bars show the 25th and 75th percentile values. Circles: summers of 1999–2001; squares: summer of 2000.

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0900–1500 LST period, and there were far fewer large values compared to those found at Barrow or Atqasuk.

4. Discussion

An explanation for the generally larger values of τ_c and LWP at Atqasuk is suggested by an examination of the dependence of LWPs on wind direction. The wind directions were measured at the top of the 40-m tower at Barrow. Barrow also has a radar wind profiler that can provide wind directions at higher elevations but the data recovery from the profiler was poorer, especially in 2002. In looking at the directional dependence of LWPs it is useful to consider two categories of clouds—those with low bases and those with high bases. We expect that clouds with low bases will be more likely to interact with the surface through turbulent mixing. The definition of high and low is, of course, arbitrary but it is convenient to select the median base height of the clouds at a given site as the separation point. With this criterion, low clouds at Barrow are those with base heights less than or equal to 270 m, while at Atqasuk the corresponding value is 450 m. We note that these definition of low and high clouds are not standard ones but it is convenient for the current analysis. A choice of different separation points for high and low clouds, for example, using 25th percentile values for the low cloud heights and 75th percentile values for the high cloud heights, yields generally similar results. Figure 5 shows the median LWPs at Atqasuk and Barrow as a function of wind direction for two cases, one where low clouds were found at either site, and the second where high clouds were found at both sites. In the first case, selecting for low clouds at either site allows for the possibility of a low cloud being present at one site but dissipating as the air mass moves to the second site, or alternatively, no low cloud being present at one site but one forming as the air mass is en route to the second site. Either of these possibilities might be brought about through air–surface interactions. Conversely, with high clouds at both sites such interactions are less likely to be important.

With this separation several features stand out. First, the differences in LWPs are generally somewhat larger for low clouds than for high ones. Second, for low clouds the LWPs at Atqasuk are higher than those at Barrow for all wind directions with the exception of the sector centered on 135°, where the Barrow value is larger than the Atqasuk one, and those at 180° and 225°, when the values at the two sites are essentially the same. This is in contrast to the high cloud-base cases where the differences in LWP show no particular consistency from one wind sector to the next. Third, in the

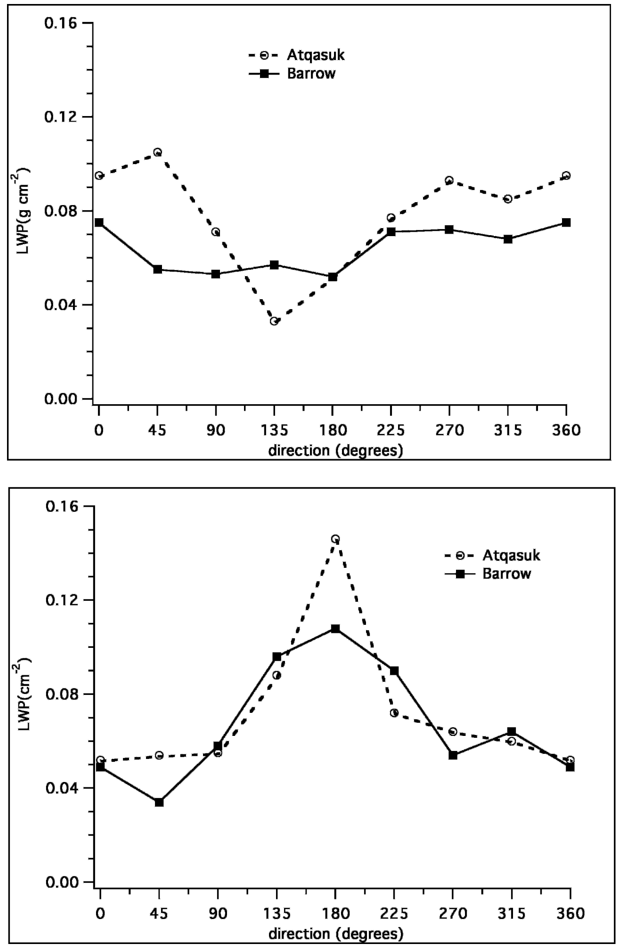

FIG. 5. Variation of LWPs with wind direction for (top) low clouds and (bottom) high clouds at Barrow and Atqasuk.

low cloud case, the LWPs at Barrow change relatively little with wind direction compared to the changes at Atqasuk; in the higher cloud data both Barrow and Atqasuk LWPs show pronounced variations.

Figure 6 summarizes the variation of the differences in Atqasuk and Barrow LWP values for low clouds with a schematic diagram that illustrates the wind direction sectors with positive differences and those with negative or minimal differences. For wind directions in which the upwind fetch at Barrow is predominantly over the ocean, the LWPs there are smaller than those at Atqasuk, where the upwind fetch includes a significant distance over tundra and lakes. When the upwind fetch at Barrow includes extensive travel over land (135°, 180°, and 225° sectors), the median Barrow LWP is larger than or similar to the median LWP at Atqasuk (cf. Fig. 5). For the high cloud-base case, no such orderly distinction can be made.

These results suggest that interactions with the surface may affect the LWPs of low-level clouds at the

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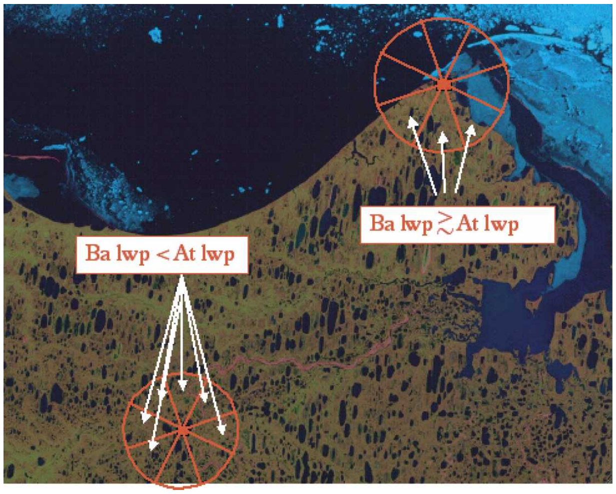

FIG. 6. Schematic diagram showing wind direction octants for which low cloud LWPs at Barrow are (left) less than and (right) greater than or equal to those at Atqasuk.

North Slope, but the mechanisms are as yet uncertain. There are two ways in which arctic clouds can interact with the surface. One is through radiative transfer, and numerous studies have indicated that this is the dominant mechanism between clouds and sea ice during the summer (e.g., Curry et al. 1996). The other is through turbulent mixing. We propose that turbulent mixing is the primary mechanism for cloud–surface interactions in summertime clouds over the tundra and that these interactions play an important role in modifying the cloud properties between Barrow and Atqasuk.

One might imagine that turbulence could modulate boundary layer clouds over the tundra through several mechanisms. Consider an arctic cloud layer, possibly decoupled from the surface, being advected from ocean to tundra. During the summer, the albedo of the tundra is much lower than the ice pack. This, combined with a lower heat capacity for the soil and vegetation than for the nearby ocean, leads to an appreciably warmer surface over the tundra. This warmer surface in turn generates convective turbulence that warms the boundary layer and couples the low clouds to the surface, perhaps even causing a jump in cloud-base height in the immediate vicinity of the coast. By itself, warming would lower relative humidity in the boundary layer and lead to the dissipation of clouds as they move inland. However, despite exposed soil and vegetation, the tundra is not dry. Rather it is covered by numerous lakes and melt ponds, amounting to approximately 25% (A. Ciallela, Brookhaven National Laboratory, 2001, personal communication) of the surface area. These water bodies are also likely to be considerably warmer than the ocean water, especially for shallow lakes or melt ponds that are warmed by the tundra. This results in higher mixing ratios inland than near the coast, as can be seen in histograms of mixing ratio distributions at Barrow and Atqasuk (not shown). We hypothesize that the enhanced upward fluxes of water vapor more than compensate for the warming of the boundary layer and hence increase cloud water content as the clouds move inland from the coast. This mechanism allows for entrainment that deepens the boundary layer and raises both cloud bases and cloud tops. The conceptual model also applies to air advecting from Atqasuk to Barrow. In this case, water vapor is similarly added to the boundary layer during the passage over the tundra with the result that for southerly wind directions the Barrow clouds have LWPs comparable to or greater than those at Atqasuk.

This explanation is further supported by a consideration of the surface sensible and latent heat fluxes shown earlier in Fig. 4. The differences in the flux values at Barrow and Atqasuk, while small, are consistent with what would be expected from air that warms and moistens as it moves inland from the coast. A considerably larger difference is obtained by comparing the sensible heat fluxes at Barrow and Atqasuk with those at Doctor Island, especially for the period 0900–1500 LST. For these times the median values for the sensible heat fluxes at Barrow and Atqasuk are 93 and 105 W m^{-2}, respectively, while that at Doctor Island is close to zero. A negligible heat flux at Doctor Island is consistent with our hypothesis that the surface energy balance over the cold water and ice offshore from Barrow is far less likely to produce moist convective conditions compared to the energy balance over land and inland lakes. On the other hand, upward sensible heat fluxes on the order of 100 W m^{-2} are sufficient to induce some convection. Although in our study the clouds at both sites appear to be primarily stratiform, it is even possible for convective clouds to develop over arctic land surfaces, as has been noted by other investigators (Vowinckel and Orvig 1970; Maxwell 1980, 1982). These results also show that surface flux measurements taken only a kilometer or so inland from the coast may not adequately represent the surface conditions that affect coastal cloud properties during onshore wind conditions.

Stage and Businger (1981) and Brümmer (1997) present analyses of cold air outbreaks over Lake Ontario and over the Fram Strait and Norwegian Sea, respectively, and flows from the Arctic Ocean over the North Slope have some similarities to their cases. Their work shows that a complete explanation of the evolution of the downwind boundary layer and clouds requires a consideration of a variety of mechanisms, in-

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cluding turbulent surface fluxes, cloud-base and -top radiation, condensation, and evaporation, and entrainment. Such an analysis is well beyond the scope of this paper but it is possible to construct a simple model that illustrates the likely importance of the surface turbulent flux component to the evolution of cloud properties.

We wish to compute the change in the water content of a column of air that extends from the surface to the top of the cloud layer as that column moves from the coast to an inland location. We assume that turbulent heat and moisture fluxes at the surface will cause the boundary layer to grow and the thickness of the cloud to increase, and that any changes in the water content will be restricted to this column depth. To carry out such a calculation we need some estimate of the cloud heights at the two locations. We further restrict ourselves to low cloud conditions when surface turbulent fluxes are more likely to affect cloud properties. Under low cloud conditions, the median 2-m temperature at Barrow was ~0.8°C, the median base height of the low clouds was 140 m, and the median LWP was 0.065 g m^{-2}; the corresponding values for Atqasuk were 3.0°C, 240 m, and 0.122 g m^{-2}, respectively. Using the adiabatic parcel approximation (e.g., Miller et al. 1998), we can calculate the thickness of the cloud required to produce the observed value of LWP; we can then compute the total water mass from the surface to the cloud top. For the conditions described above the calculated difference in the total mass of water from the surface to cloud top at the two sites is 1.20 kg m^{-2}.

We wish to compare this value with the amount of water that would be injected into the atmosphere by surface latent heat fluxes as the air column travels inland. For the 6-h period between 0900 and 1500 LST, the median latent heat flux from the FLUXNET stations at Barrow and Atqasuk was approximately 62 W m^{-2}. Six hours is also roughly the time required for air to move from the coast inland to Atqasuk for the prevailing wind speeds and directions at the North Slope. Such a flux for this period of time results in the addition of approximately 0.54 kg m^{-2} to the atmosphere, which is almost half of the value of the increased mass calculated above.

There are, of course, a number of assumptions and simplifications in such a model that would warrant a more careful treatment in a complete modeling study. These include the likelihood that the actual latent heat fluxes over the North Slope might well be larger because of the prevalence of numerous lakes in the region whose fluxes were not measured (Boudreau and Rouse 1995; Rouse 2000; Eaton et al. 2001), the likelihood that fluxes would be smaller during periods of low clouds compared to the value found for all conditions, the assumption of a constant total water mixing ratio from the ground to the top of the low cloud layer, the failure to include possible additional condensation induced by cloud-top radiative cooling, etc. Despite these limitations, the simple model used here suggests that the turbulent surface fluxes are indeed an important factor that contributes significantly to the differences in cloud properties between coastal and inland sites.

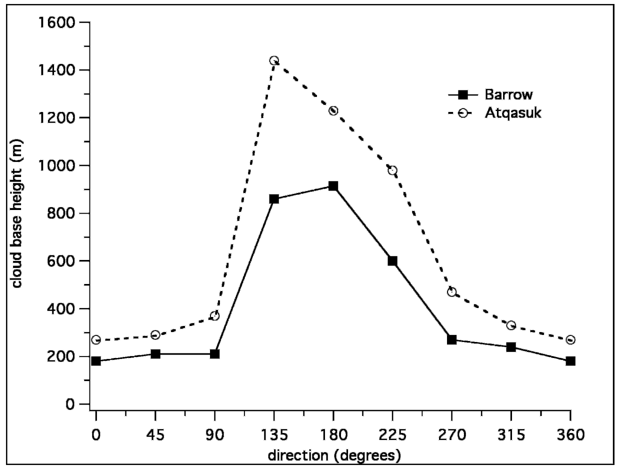

FIG. 7. Variation of median cloud-base height at Barrow and Atqasuk as a function of wind direction.

The development of convergence zones near coastal areas are also known to affect cloud formation (e.g., Koračin and Dorman 2001) and may be important here as well, but several features suggest that they are not sufficient to explain the observed differences in cloud optical properties between Barrow and Atqasuk. First, the topography of the North Slope is quite flat. The elevation of Atqasuk is only 20 m, so orographic effects should be minimal. Next, the winds are onshore approximately 80% of the times so that convergence of possible sea breezes and prevailing winds will also be minimized (Gilliam et al. 2004). Under such conditions but in the absence of convection, clouds 60 km inland would not generally be expected to have higher water content than those nearer the coast, as is observed. Finally, the larger mixing ratios found inland are consistent with moistening of the atmosphere by surface latent heat fluxes but are not readily explained by convergence or other synoptic effects.

A puzzling aspect of the data is the variation of LWPs with wind direction for high clouds. For high clouds the LWP values at Barrow in the 135° to 225° sectors are significantly larger than for low clouds (Fig. 5), and at 180° the same is true for Atqasuk. Figure 7 shows the variation of median cloud-base heights at Barrow and Atqasuk as a function of wind direction. Clouds with higher base heights are more prevalent in

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the 135° to 225° sectors than for other wind directions, which almost certainly arise from differences in the synoptic systems responsible for the clouds, and it is for these same sectors that the LWPs for high clouds show marked increases at both sites. The median Atqasuk LWP for the 180° sector is about 35% larger than the Barrow LWP. At this point we are unable to offer a definitive explanation for this behavior. Given the relatively small separation of the two sites, it seems unlikely that synoptic-scale systems are responsible for the differences in LWPs. One possibility is that the wind directions at 40 m differ significantly from those higher up, which is possible under the stratified conditions found above a relatively shallow mixed layer. We speculate that a more likely explanation is that convective clouds with relatively large values of LWP may originate in the higher terrain of the Brooks Range to the south and subsequently begin to dissipate as the air subsides on its way toward the lower terrain to the north, but additional study is needed to confirm this possibility.

Finally, the similarity of the effective droplet radii at the two sites seen in Fig. 3 is curious. If the clouds become deeper as they move inland from the coast, their liquid water paths and optical depths would be expected to increase. Brenguier et al. (2000) discuss the dependence of effective radii on cloud depth h and droplet number density N for adiabatic clouds. They show that $r_e(h) \propto (h/N)^{1/3}$; thus, if the cloud depth increases, the effective radii would increase unless N also increases to maintain the h to N ratio. However, the dependence of r_e on h is a weak one. Returning to the simple model presented earlier, we find that the cloud thickness at Atqasuk need only be about 34% larger than at Barrow to account for the LWP differences. This means that r_e would only be about 10% larger for a constant N, which is comparable to the estimated accuracy of our r_e results. Unfortunately we have no direct observations of either h or N, and we are unable to say whether the similarity of the effective droplet radii at the two sites has any real significance.

5. Summary and conclusions

We have carried out an analysis of cloud properties at two sites on the North Slope of Alaska during the warm seasons for three years, 2001–03. The coastal site, Barrow, is separated from the inland site, Atqasuk, by only about 100 km but there are significant differences in the cloud characteristics. There are more clear hours at Atqasuk than at Barrow, but the clouds at Atqasuk have greater optical depths and the low clouds tend to have greater LWPs. In contrast, the distributions of effective droplet radii for clouds at the two sites appear similar. We conclude that observations at Barrow are often not adequate to characterize cloud conditions at Atqasuk, at least during periods of the prevailing onshore flows.

We hypothesize that turbulent coupling of the atmosphere to the underlying surface is an important factor contributing to the differences in cloud properties. The relatively warm (compared to the ocean or offshore ice) and wet tundra provides a source of heat and moisture that warms and deepens the boundary layer, increases the cloud water content, and raises cloud bases and tops. For onshore flows this should result in optically thicker clouds at Atqasuk than at Barrow; offshore flows will tend to have the opposite effect. The effect is expected to be less pronounced or absent for clouds with higher cloud bases, and both of these features are found in the data. Additional support for this hypothesis is found from a set of surface sensible heat flux measurements taken during the summer of 2000 that show markedly larger fluxes over the tundra than over the ocean, and by distributions of mixing ratios, which show higher values inland than near the coast. A simple model offers further support for this hypothesis.

If the behavior found over the NSA is characteristic of other arctic coastal regions, then the differences in cloud properties between coastal or offshore locations and sites only ~100 km inland will pose a significant challenge for climate model simulations.

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REFERENCES

Auble, D. L., and T. P. Meyers, 1992: An open path, fast response infrared-absorption gas analyzer for H_2O and CO_2. *Bound.-Layer Meteor.,* **59,** 243–256.

Unauthenticated | Downloaded 10/17/21 12:00 PM UTC

Baldocchi, D. E., and Coauthors, 2001: FLUXNET: A new tool to study the temporal and spatial variability of ecosystem–scale carbon dioxide, water vapor, and energy flux densities. *Bull. Amer. Meteor. Soc.,* **82,** 2415–2434.

Barnard, J. C., and C. N. Long, 2004: A simple empirical equation to calculate cloud optical thickness using shortwave broadband irradiances. *J. Appl. Meteor.,* **43,** 1057–1066.

——, J. C. Doran, S. Zhong, and C. N. Long, 2001: A comparison of cloud properties at Barrow and Sheba during the summer of 1998. Preprints, *Sixth Conf. on Polar Meteorology and Oceanography*, San Diego, CA, Amer. Meteor. Soc., 232–235.

Beesley, J., and R. E. Moritz, 1999: Toward an explanation of the annual cycle of cloudiness over the Arctic Ocean. *J. Climate,* **12,** 395–415.

Boers, R., 1997: Simultaneous retrievals of cloud optical depth and droplet concentration from solar irradiance and microwave liquid water path. *J. Geophys. Res.,* **102** (D25), 29 881–29 891.

Boudreau, L. D., and W. R. Rouse, 1995: The role of individual terrain units in the water balance of the wetland tundra. *Climate Res.,* **5,** 31–47.

Brenguier, J.-L., H. Pawlowska, L. Schüller, R. Preusker, J. Fischer, and Y. Fouquart, 2000: Radiative properties of boundary layer clouds: Droplet effective radius versus number concentration. *J. Atmos. Sci.,* **57,** 803–821.

Brümmer, B., 1997: Boundary layer mass, water, and heat budgets in wintertime cold-air outbreaks from the Arctic sea ice. *Mon. Wea. Rev.,* **125,** 1824–1837.

Curry, J. A., W. B. Rossow, D. Randall, and J. L. Schramm, 1996: Overview of Arctic cloud and radiation characteristics. *J. Climate,* **9,** 1731–1764.

——, and Coauthors, 2000: FIRE Arctic Clouds Experiment. *Bull. Amer. Meteor. Soc.,* **81,** 5–29.

Dong, X., and G. G. Mace, 2003: Arctic stratus cloud properties and radiative forcing derived from ground-based data collected at Barrow, Alaska. *J. Climate,* **16,** 445–461.

——, T. P. Ackerman, E. E. Clothiaux, P. Pilewskie, and Y. Han, 1997: Microphysical and radiative properties of boundary layer stratiform clouds deduced from ground-based measurements. *J. Geophys. Res.,* **102** (D20), 23 829–23 844.

Doran, J. C., S. Zhong, J. C. Liljegren, and C. Jakob, 2002: A comparison of cloud properties at a coastal and inland site at the North Slope of Alaska. *J. Geophys. Res.,* **107,** 4120, doi:10.1029/2001JD000819.

Eaton, A. K., W. R. Rouse, P. M. Lafleur, P. Marsh, and P. D. Blanken, 2001: Surface energy balance of the western and central Canadian Subarctic: Variations in the energy balance among five major terrain types. *J. Climate,* **14,** 3692–3703.

Gilliam, R. C., S. Raman, and D. D. S. Niyogi, 2004: Observational and numerical study of the influence of large-scale flow direction and coastline shape on sea-breeze evolution. *Bound.-Layer Meteor.,* **111,** 275–300.

Gultepe, I., G. Isaac, D. Hudak, R. Nissen, and J. W. Strapp, 2000: Dynamical and microphysical characteristics of Arctic clouds during BASE. *J. Climate,* **13,** 1225–1254.

Harrison, L., J. Michalsky, and J. Berndt, 1994: Automated multifilter rotating shadow-band radiometer—An instrument for optical depth and radiation measurements. *Appl. Opt.,* **33,** 5118–5125.

Hobbs, P. V., and A. L. Rangno, 1998: Microstructures of low and middle-level clouds over the Beaufort Sea. *Quart. J. Roy. Meteor. Soc.,* **124,** 2035–2071.

Kahl, J. D., M. C. Serreze, and R. C. Schnell, 1992: Tropospheric low-level temperature inversions in the Canadian Arctic. *Atmos.–Ocean,* **30,** 511–529.

——, N. A. Zaitseva, V. Khattatov, R. C. Schnell, D. M. Bacon, J. Bacon, V. Radionov, and M. C. Serreze, 1999: Radiosonde observations from the former Soviet "North Pole" series of drifting ice stations, 1954–90. *Bull. Amer. Meteor. Soc.,* **80,** 2019–2026.

Koračin, D., and C. E. Dorman, 2001: Marine atmospheric boundary layer divergence and clouds along California in June 1996. *Mon. Wea. Rev.,* **129,** 2040–2056.

Liljegren, J. C., E. E. Clothiaux, G. G. Mace, S. Kato, and X. Dong, 2001: A new retrieval for cloud liquid water path using a ground-based microwave radiometer and measurements of cloud temperature. *J. Geophys. Res.,* **106** (D13), 14 485–14 500.

Lin, B., P. Minnis, A. Fan, J. A. Curry, and H. Gerber, 2001: Comparison of cloud liquid water paths derived from in situ and microwave radiometer data taken during the SHEBA/FIREACE. *Geophys. Res. Lett.,* **28,** 975–978.

Long, C. N., and T. P. Ackerman, 2000: Identification of clear skies from broadband pyranometer measurements and calculation of downwelling shortwave cloud effects. *J. Geophys. Res.,* **105** (D12), 15 609–15 626.

——, ——, J. J. DeLuisi, and J. Augustine, 1999: Estimation of fractional sky cover from broadband SW radiometer measurements. *Proc. 10th Conf. on Atmospheric Radiation,* Madison, WI, Amer. Meteor. Soc., 383–386.

Maxwell, J. B., 1980: *The Climate of the Canadian Arctic Islands and Adjacent Waters.* Vol. 1, Environment Canada, 532 pp.

——, 1982: *The Climate of the Canadian Arctic Islands and Adjacent Waters.* Vol. 2, Environment Canada, 589 pp.

Michalsky, J. J., F. A. Schlemmer, W. E. Berkheiser, J. L. Berndt, L. C. Harrison, N. S. Laulainen, N. R. Larson, and J. C. Barnard, 2001: Multiyear measurements of aerosol optical depth in the Atmospheric Radiation Measurement and Quantitative Links programs. *J. Geophys. Res.,* **106,** 12 099–12 107.

Miller, M. A., M. P. Jensen, and E. Clothiaux, 1998: Diurnal cloud and thermodynamic variations in the stratocumulus transition regime: A case study using in situ and remote sensors. *J. Atmos. Sci.,* **55,** 2294–2310.

Min, Q., and L. C. Harrison, 1996: Cloud properties derived from surface MFRSR measurements and comparison with GOES results at the ARM SGP Site. *Geophys. Res. Lett.,* **23,** 1641–1644.

Perovich, D. K., and Coauthors, 1999: Year on ice gives climate insights. *Eos, Trans. Amer. Geophys. Union,* **80,** 481–486.

Ricchiazzi, P., S. Yang, C. Gautier, and D. Soule, 1998: SBDART: A research and teaching software tool for plane-parallel radiative transfer in the earth's atmosphere. *Bull. Amer. Meteor. Soc.,* **79,** 2101–2114.

Rouse, W. R., 2000: The energy and water balance of high-latitude wetlands: Controls and evaporation. *Global Change Biol.,* **6** (Suppl. 1), 59–68.

Stage, S. A., and J. Businger, 1981: A model for entrainment in a cloud-topped marine boundary layer. Part I: Model description and application to a cold-air outbreak. *J. Atmos. Sci.,* **38,** 2213–2229.

Tjernström, M., C. Leck, P. Persson, G. Ola, M. L. Jensen, S. P. Oncley, and A. Targino, 2004: The summertime Arctic atmo-

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sphere: Meteorological measurements during the Arctic Ocean Experiment 2001. *Bull. Amer. Meteor. Soc.,* **85,** 1305–1321.

Uttal, T., and Coauthors, 2002: Surface heat budget of the Arctic Ocean. *Bull. Amer. Meteor. Soc.,* **83,** 255–275.

Vowinckel, E., and S. Orvig, 1970: The Climate of the North Polar Basin. *Climates of the Polar Regions*, S. Orvig, Ed., *World Survey of Climatology*, Vol. 14, Elsevier, 129–152.

Warren, S. G., C. J. Hahn, J. London, R. M. Chervin, and R. L. Jenne, 1986: Global distribution of total cloud cover and cloud type amounts over land. NCAR Tech. Note NCAR/TN-273+STR, DOE/ER/60085-H1, 29 pp. + 200 maps.

——, ——, ——, ——, and ——, 1988: Global distribution of total cloud cover and cloud type amounts over the ocean. NCAR Tech. Note NCAR/TN-317+STR, DOE/ER-0406, 41 pp. + 170 maps.

Westwater, E. R., Y. Han, M. D. Shupe, and S. Y. Matrosov, 2001: Analysis of integrated cloud liquid and precipitable water vapor retrievals from microwave radiometers during SHEBA. *J. Geophys. Res.,* **106** (D23), 32 019–32 030.

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