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A comparison of cloud properties at a coastal and inland site at the North Slope of Alaska

J. C. Doran and S. Zhong
Pacific Northwest National Laboratory, Richland, Washington, USA

J. C. Liljegren
Argonne National Laboratory, Argonne, Illinois, USA

C. Jakob[1]
European Centre for Medium-Range Weather Forecasts, Reading, England

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[1] We have examined differences in cloud liquid water paths (LWPs) at a coastal (Barrow) and an inland (Atqasuk) location on the North Slope of Alaska using microwave radiometer (MWR) data collected by the U.S. Department of Energy's Atmospheric Radiation Measurement Program for the period June–September 1999. Revised retrieval procedures and a filtering algorithm to eliminate data contaminated by wet windows on the MWRs were employed to extract high-quality data suitable for this study. For clouds with low base heights (<350 m), the LWPs at the coastal site were significantly higher than those at the inland site, but for clouds with higher base heights the differences were small. Air-surface interactions may account for some of the differences. Comparisons were also made between observed LWPs and those simulated with the European Centre for Medium-Range Weather Forecasts model. The model usually successfully captured the occurrence of cloudy periods, but it underpredicted the LWPs by approximately a factor of 2. It was also unsuccessful in reproducing the observed differences in LWPs between Barrow and Atqasuk. Some suggestions on possible improvements in the model are presented. *INDEX TERMS:* 3349 Meteorology and Atmospheric Dynamics: Polar meteorology; 3307 Meteorology and Atmospheric Dynamics: Boundary layer processes; 3322 Meteorology and Atmospheric Dynamics: Land/atmosphere interactions; 3337 Meteorology and Atmospheric Dynamics: Numerical modeling and data assimilation; *KEYWORDS:* arctic clouds, cloud liquid water, microwave radiometer, ECMWF model, air-surface interactions

1. Introduction

[2] The Arctic includes extensive land areas, and there are also large landmasses south of the Arctic Circle that experience arctic-like conditions over much of the year. Despite this, the preponderance of past studies of arctic cloud properties have focused on conditions over the ocean or near the coast [e.g., *Kukla and Robinson*, 1988; *Schweiger and Key*, 1992; *Curry et al.*, 1996; *Hobbs and Rangno*, 1998; *Beesley and Moritz*, 1999; *Gultepe et al.*, 2001; *Curry et al.*, 2000]. There has been relatively less attention paid to differences between the cloud characteristics over the ocean or coast and those farther inland. *Herman and Curry* [1984] and *Curry and Herman* [1985] describe late spring and early summer aircraft measurements of liquid water content, droplet size distribution, and other microphysical properties of stratus clouds over the Beaufort Sea, and they used a radiative transfer model to investigate the relationships between the radiative properties of the clouds and cloud microphysics. More recently, increased emphasis has been given to the study of ice or mixed-phase clouds [e.g., *Curry et al.*, 1996; *Randall et al.*, 1998; *Stamnes et al.*, 1999; *Curry et al.*, 2000]. Long-term data for detailed comparisons of observed and predicted arctic cloud properties at both coastal and inland sites during the warmer months of the year, however, have not been generally available.

[3] There are reasons to expect that cloud properties at coastal and inland sites can differ. At the North Slope of Alaska, for example, the prevailing winds are from the east and generally onshore so that the clouds found there are often representative of those found over the adjacent water or ice [*Maykut and Church*, 1973]. In contrast, at inland locations, clouds associated with winds from an easterly direction may travel hundreds of kilometers or more over land. This additional passage over land is unlikely to be important in the winter when the sea is frozen, the land is covered by snow, and clouds are normally not coupled to the surface through turbulence [*Curry et al.*, 1996]. In the warmer months,

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[1] Now at Bureau of Meteorology Research Centre, Melbourne, Australia.

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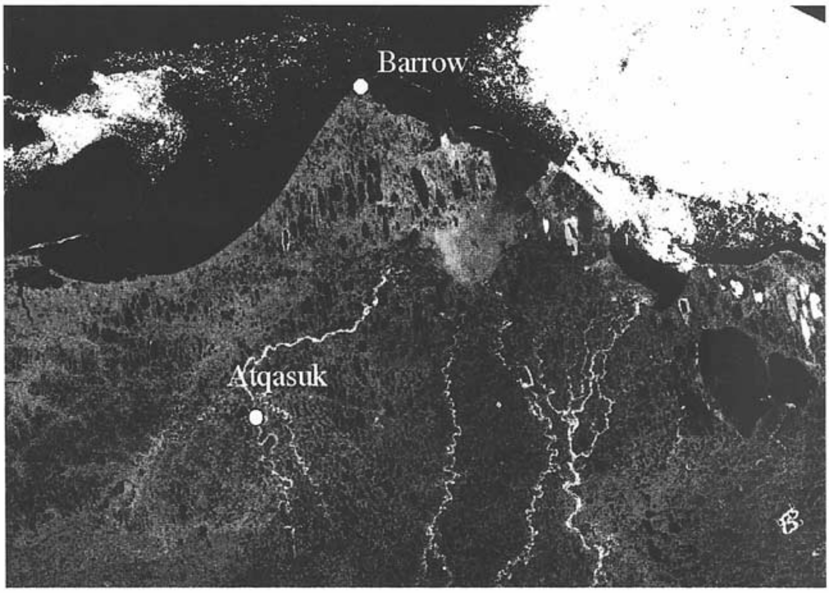

Figure 1. North Slope of Alaska and locations of Barrow and Atqasuk.

however, when the sea has open water and the snow has melted over land, turbulent coupling to the surface can be more important. For example, *Kahl et al.* [1992] found that the height of inversion bases in the Canadian Arctic tended to lift during the summer, with mixed layers developing beneath the inversions. This increases the likelihood that air-surface interactions will affect the properties of boundary layer clouds as one moves inland from the coast. Thus the potential exists for substantial differences in cloud and radiation fields between coastal and inland sites.

[4] The proper treatment of arctic coastal-inland transition zones can also be a severe test for the performance of models, and an assessment of how well they perform in such circumstances would provide a good opportunity to evaluate a number of important features of their parameterization schemes.

[5] To examine these issues, we conducted a study of differences in coastal and inland cloud characteristics using data collected at two sites, Barrow and Atqasuk, in Alaska. Barrow is on the coast of the North Slope and Atqasuk is an inland site. We began by examining the liquid water paths (LWPs) measured by microwave radiometers (MWRs) at these two locations for the period June–September of 1999. Our objectives were (1) to determine whether the LWP values at the Barrow and Atqasuk sites were significantly different and under what circumstances such differences might arise, and (2) to test the ability of the European Centre for Medium-Range Weather Forecasts (ECMWF) model to simulate the properties of clouds at these sites and to reproduce any observed differences between Barrow and Atqasuk. To the extent that the model might be successful in doing so, it could then be used as an analysis tool to help explain why such differences occur.

2. Sites and Instrumentation

[6] The North Slope of Alaska/Adjacent Arctic Ocean (NSA/AAO) site [*Stamnes et al.*, 1999] is one of three Cloud and Radiation Testbeds (CARTs) operated by the U.S. Department of Energy's Atmospheric Radiation Program (ARM). The CARTs have been designed for conducting both long-term and intensive measurements of cloud properties, longwave and shortwave radiation, meteorological variables, and surface properties to study the effects and interactions of sunlight, radiant energy, and clouds on temperatures, weather, and climate [*Stokes and Schwartz*, 1994]. CART data have been used to test, evaluate, and improve the performance of single-column models, cloud resolving models, and general circulation models (GCMs) used in climate studies [*Randall and Xu*, 1996].

[7] Because the size of a grid cell in a GCM may be on the order of 100 km or more, it is important to determine to what extent meteorological and radiometric observations made at one location in a CART are representative for the CART as a whole. Thus CARTS have multiple measurements locations. At the NSA/AAO CART the principal complement of instruments is located at Barrow on the northern coast of Alaska (71.30°N, 156.68°W). A second (but more limited) set of instruments has been installed at the village of Atqasuk (70.47°N, 157.40°W), approximately 100 km inland to the southwest. Figure 1 shows the locations of these sites.

[8] Both Barrow and Atqasuk were equipped with dual-channel MWRs (Radiometrics Corporation, Boulder, Colorado) that measure equivalent blackbody brightness temperatures at 23.8 GHz and 31.4 GHz. From these two measurements the ARM MWR (http://www.arm.gov/docs/instruments/static/mwr.html) determines a value of the water vapor path (WVP) and the LWP every 20 to 30 s, depending on the operating mode of the instrument. Details of its characteristics and operating procedures are given by *Liljegren* [1994, 1999a].

[9] The noise level of the radiometer is low, approximately 0.003 mm (3 g m^{-2}). The WVP and LWP values generated in the current standard ARM processing are based on a statistical retrieval technique [*Westwater*, 1993] and the

Liebe and Layton [1987] and *Grant et al.* [1957] absorption models. The RMS error for individual LWP values is higher than the noise level when a statistical retrieval procedure is used, because such a retrieval is based on a mean cloud radiating temperature and on retrieval coefficients that are assumed to vary only on a monthly basis. In practice, of course, there will be variations in these quantities on diurnal scales, leading to an RMS error estimated at 0.03 mm (30 g m^{-2}) [*Liljegren*, 1999b] at the North Slope in July. In this paper, however, we will only compare LWP distributions computed over periods of a month or even longer. Because of this, and because diurnal deviations from monthly mean values of cloud radiating temperatures and their associated retrieval coefficients are likely to be similar at two sites located only 100 km apart, the relative accuracy of month-long mean LWP values from Barrow and Atqasuk will be closer to the noise level than to the RMS value for an individual measurement given above. We will comment further on the significance of some of the differences that were found between Barrow and Atqasuk later in this paper (section 4).

[10] Also located at Barrow was a Vaisala CT25 ceilometer for measuring cloud base heights, and some of those data are used in our analysis as well. The operating range for this instrument is 7.6 km with a vertical resolution of 15 m. Details can be found at http://www.arm.gov/docs/instruments/static/vceil.html. Additional instruments (e.g., a cloud radar at Barrow, a ceilometer at Atqasuk, and rotating shadowband radiometers at both Barrow and Atqasuk) are now available and will be available for future studies, but the MWRs were the only instruments operating at both sites in 1999 that provided the kind of data we required for comparisons of cloud properties.

3. Data Quality and Processing

[11] Accurately measuring LWPs with the ARM MWRs in an arctic environment can be challenging, even during the June–September time period when the cloud liquid water content is considerably higher than during midwinter. It is not surprising, then, that there has been some controversy arising from comparisons of MWR LWP values with aircraft-derived values obtained during the Surface Heat Budget of the Arctic Ocean (SHEBA) [*Perovich et al.*, 1999] campaign; MWR-derived values of LWP have been reported as being as much as a factor of 2 too large [*Curry et al.*, 2000]. As a result, there has been considerable scrutiny of the retrieval procedures used to convert MWR-measured brightness temperatures to WVP and LWP values.

[12] *Liljegren* [1998], *Liljegren et al.* [2001], *Lin et al.* [2001], and *Westwater et al.* [2001] have all shown how the accuracy of a statistical LWP retrieval can be improved using physically based algorithms that take into account improved estimates of the cloud temperatures. Results from these physically based retrievals show that the use of a statistical retrieval to calculate the LWP for an arbitrary time period with a duration of, for instance, a few minutes or tens of minutes, can be somewhat inaccurate. In contrast, errors associated with averages over longer periods, such as the month- or season-long periods we are dealing with in this paper, should be small. Thus we believe that the use of statistical retrieval techniques is appropriate for our purposes. Moreover, in 1999 some of the additional information required for the application of these physically based techniques was available only at Barrow and not at Atqasuk.

[13] A more troublesome issue has been the selection of the appropriate absorption coefficients used in the retrieval algorithms. In addition to the models used in the ARM retrievals given above, *Westwater et al.* [2001] also considered the measurements of *Rosenberg* [1972] and the more recent work of *Liebe et al.* [1991] and *Rosenkranz* [1998]. Using data from SHEBA, they showed how the use of different combinations of radiation models can affect the retrieved values of LWP. The differences in the absorption coefficients among the models they investigated were generally small for temperatures above 273 K but became larger at temperatures below 273 K in which supercooled cloud water is found. Their revised results gave considerably better agreement between the MWR and aircraft-derived LWP values. *Lin et al.* [2001] developed their own retrieval based on yet another microwave radiative transfer model and different liquid water and gas absorption coefficients. Their method reduced the LWP values generated by the standard ARM retrievals by almost a factor of 2 for the thin and moderate clouds sampled during the SHEBA flights and used for comparisons with MWR data, so that the agreement between the MWR and aircraft measurements was much improved. Summarizing the effects of the new retrieval solely in terms of a fixed ratio such as this, however, can be misleading. The magnitudes of the differences in LWP values obtained by using different sets of absorption coefficients are not particularly big, but if the LWPs are small, the correction factors can be large. For example, an examination of the results from *Westwater et al.*'s [2001] reanalysis shows that ratios of old to new LWP values were large when the LWPs were small (e.g., a factor of approximately 2 for LWPs between 0.01 and 0.015 mm) but considerably smaller for larger values of LWP (e.g., only about 20% for LWPs between 0.10 and 0.12 mm.)

[14] Because the LWP values for arctic clouds are often small, we did not use the standard archived ARM values in this paper. Instead, we followed the approach of *Westwater et al.* [2001] and recomputed all of the LWPs on the basis of the coefficients taken from *Liebe et al.* [1991] and *Rosenkranz* [1998]. Although some uncertainties may still remain in the extraction of LWP values from the MWR, they should be small and should not affect any of the conclusions in this paper. As an example, the median LWP values for Barrow and Atqasuk were each about 34% higher when computed with the original ARM retrieval compared with the revised one, but the relative behavior of the LWPs at the two sites (see below) is largely unchanged.

[15] Care also had to be taken to identify and eliminate data collected during periods when the window on the MWR may have been wet. The MWR was equipped with a blower and a heater to help remove water that collects on the window from precipitation or condensation. The blower operated continuously, but the heater was only turned on when a sensor indicated the presence of water. A data flag was set when the heater was on to indicate the wet-window condition and the operation of the heater. The response of the sensor to wetness is dependent on temperature, however, and adjustments need to be made regularly for optimum operation. In practice, this was not always done, and the

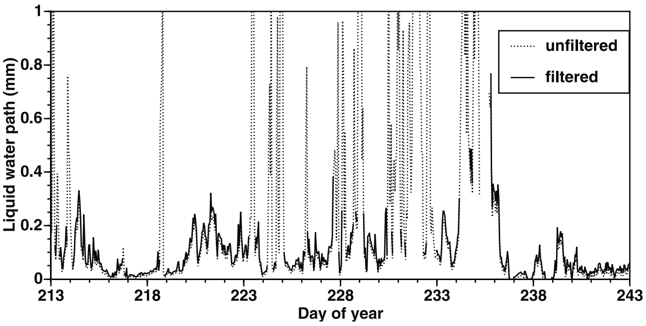

Figure 2. Comparison of retrieved liquid water path values before and after the application of the wet-window filtering algorithm.

wet-window flag was sometimes set when the window was actually dry or failed to set when the window was wet. Accordingly, an objective procedure has been developed to identify probable wet-window conditions by monitoring the time series of both the WVP and LWP channels of the MWR. The algorithm flags instances when the variance in the WVP signal suddenly increased and the LWP values were high, indicating likely precipitation. It also flags periods when the variance of the WVP was small but the LWP remained large (greater than 1 mm), which can occur if the window had not yet completely dried. Data obtained during these times are rejected. Figure 2 gives an example of a time series of LWP before and after the application of this filtering algorithm. The algorithm removes a large fraction of the occurrences of anomalously high values of LWP, which are indicated by the spikes in the time series. The penalty, of course, is that there are corresponding gaps in the time series where the suspect data were discarded. Even with the use of this screening procedure, however, occasional values of LWP were passed that appear implausible for most nonprecipitating arctic clouds (e.g., greater than 0.25 mm (250 g m^{-2}) [*Lin et al.*, 2001]). In calculating means, we therefore have eliminated LWPs with values greater than 0.25 mm. This corresponds to a little over 2% of the data collected at Atqasuk and less than 2% of that collected at Barrow. Moreover, in our analyses we prefer to use median rather than mean values to characterize LWPs because a median value will be less sensitive to residual outliers than a mean.

[16] In our analyses the 20–30 s LWP data were normally averaged for periods of 1 hour, and distributions of LWP values were calculated using these 1-hour averages. An hourly averaged value was retained only if more than 90% of the data in a given hour passed the screening algorithm. Data from the MWR were analyzed for the period from 1 June through 30 September at both Barrow and Atqasuk. There were several extended periods of missing data (i.e., one or more days) at both sites, arising from instrument malfunctions, water on the windows that rendered the data unacceptable, or other installation or operational problems. As a result, out of 2928 possible hours of data, we obtained 2627 hours of data at Barrow and 2006 hours at Atqasuk. In comparing the observed LWP values for the two sites, however, we thought it appropriate to compare distributions of values only for time periods when both instruments were operating. If one instrument was not functioning for an extended period of time (e.g., 24 hours), then the data from both instruments were excluded from further analysis. If the data gap for one instrument was only a few hours, the data from the other instrument were retained. In this way the inclusion of data from particularly cloudy or clear days at one site, when the instrument at the other site was not operating, would be less likely to bias the comparison.

4. Results

[17] Some properties of the distributions of LWPs for each of the four months are summarized in Table 1. It is evident that there were substantial changes in the mean and median values over the course of the study period. The LWPs at both Barrow and Atqasuk were greater during the last two months than during the first two, a result consistent with the findings of the trends with time of optical depths at Barrow reported by *Leontyeva and Stamnes* [1994]. In June the median LWP value at Barrow was only about 39% of that at Atqasuk but in September was about 16% higher. On the basis of the Mann-Whitney U test [*Conover*, 1980], the medians are significantly different at the 5% level for June, July, and September; for August, there is no significant difference even at the 10% level.

[18] As we explained in section 1, we believed that cloud properties might be sensitive to the local surface or upwind fetch conditions, which differ markedly between Barrow and Atqasuk. Any such sensitivity would presumably be more apparent for low clouds than for high ones, because a mixed layer developing over land would be expected to be relatively shallow. In addition, the cloud properties would presumably show some dependence on the direction of the prevailing winds. Winds that were generally offshore at both Barrow and Atqasuk would have similar upwind fetches, but for onshore flows the upwind fetch at Barrow would be very different from the upwind fetch at Atqasuk.

Table 1. Mean, Median, and Standard Deviations of LWPs at Barrow and Atqasuk

Period	Barrow				Atqasuk			
	Mean, mm	Median, mm	Standard Deviation, mm	Hours of Data	Mean, mm	Median, mm	Standard Deviation, mm	Hours of Data
June	0.026	0.013	0.034	452	0.045	0.033	0.046	423
July	0.044	0.028	0.046	566	0.043	0.023	0.051	559
August	0.065	0.050	0.055	414	0.061	0.047	0.054	361
September	0.059	0.050	0.050	581	0.054	0.043	0.053	567
June–September	0.048	0.034	0.047	2013	0.050	0.036	0.051	1910

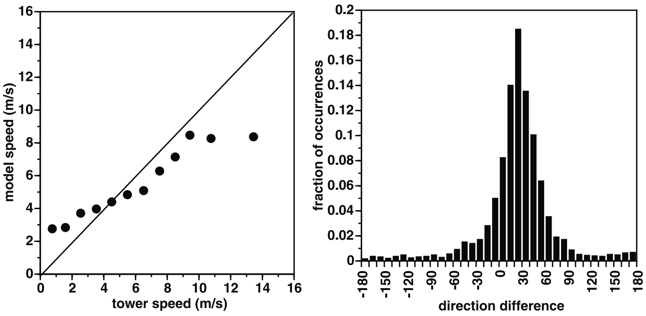

Figure 3. Comparison of modeled and measured wind speeds (left) and directions (right). The wind speed symbols are median values for selected tower speed intervals.

[19] Cloud base heights at Barrow were measured with a ceilometer, and wind speed and direction data aloft were available from twice-per-day standard rawinsonde soundings. We also had hourly averages of temperatures, wind speeds, and directions at several levels of a 40-m tower. Unfortunately, there were no soundings or tower data at Atqasuk. The Barrow rawinsonde soundings covered a greater altitude range than the tower, but they did not have sufficient temporal resolution for our purposes. The tower record had higher temporal resolution but only extended to 40 m, and it suffered from several periods of missing data, particularly in August and September. We therefore hoped to use the ECMWF model winds in our analysis. We compared the model results with the available tower data at 40 m and found that, although the mean difference and RMS error of the wind speeds were reasonably small, the model tended to overpredict speeds when the speeds were low and underpredict them at higher values. In addition, there was a mean bias in the wind directions of approximately 25°. These results are depicted in Figure 3. In view of these discrepancies we chose to use the tower data at Barrow to specify wind directions despite its height limitations and periods of missing data.

[20] Histograms of the hourly wind directions at the 40-m level at Barrow for the June–September 1999 time period are shown in Figure 4 for two categories of cloud base height, one with base heights less than 350 m and the second with base heights greater than 350 m. These heights were chosen because approximately half of the cloud base heights measured by the ceilometer fell into each category. For the lower clouds, there is a pronounced peak between 90° and 135°and smaller ones between 45° and 90° and 270° and 360°. For the higher clouds, there is again a peak in the 90° to 135° sector, but there is also a large secondary peak in the range 270° to 315°. The variation of median cloud base height for all clouds as a function of wind direction is shown in Figure 5. Together, Figures 4 and 5 clearly show the preponderance of low clouds for the most commonly occurring wind directions in the 45° to 135° range, with higher clouds becoming relatively more common for winds between 270° and 315°. Winds from these sectors account for approximately two thirds of the cases shown.

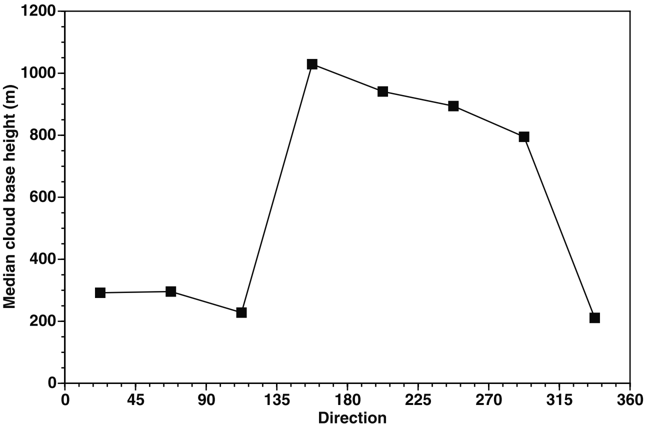

Figure 5. Variation of median cloud base height as a function of wind direction at Barrow.

[21] In Figure 6 we plot the variation of median LWPs at Barrow and Atqasuk as a function of wind direction for our two categories of cloud base height. When the cloud bases are low, Barrow has higher LWPs than Atqasuk for the most common wind directions, especially in the sector 45° to 135°. For this sector, which accounts for roughly half of all the low clouds, the median LWP at Barrow is about 35% higher than at Atqasuk. The difference is significant at the 5% level. The pronounced peak in the median LWPs in the 180° to 270° sector is produced by only a small number of events, amounting to roughly 5% of the total. Conversely, for the higher cloud bases in the most populated 45° to 135° and 270° to 315° sectors, Atqasuk's median LWPs average about 12% higher than Barrow's. The LWPs at Barrrow are considerably higher in the 180° to 270° sectors, but, again, there are relatively few occurrences there.

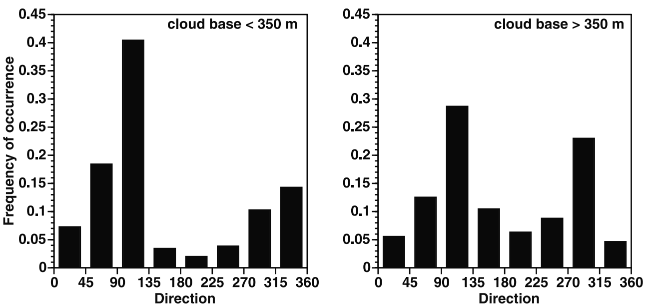

Figure 4. Histograms of wind directions for low (<350 m) and high (>350 m) cloud base heights at Barrow.

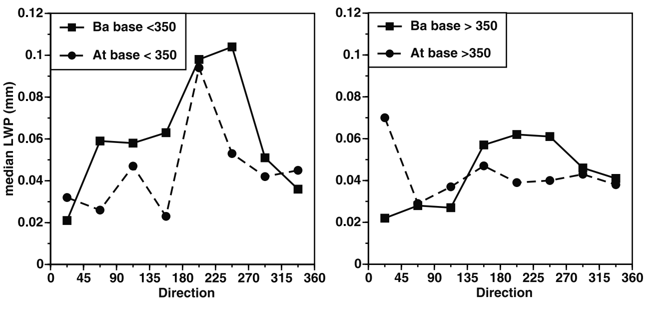

Figure 6. Variation of liquid water paths (LWP) with wind direction for clouds with low base heights (left) and high base heights (right).

[22] Winds with directions lying in the 45° to 135° range may be characterized as generally onshore flows with an upwind fetch that passes predominantly over the ocean and relatively little land before arriving at Barrow. At Atqasuk, however, there is a longer fetch over land for these directions, and it is plausible to suggest that this accounts, at least in part, for the larger LWP values at Barrow for low clouds. Sensible heat flux measurements made in the early summer of 2000 [*Shaw et al.*, 2001] show that the fluxes over land at Atqasuk are considerably higher than those over the ocean near Barrow, which would lead to enhanced mixing and a warmer and deeper boundary layer at Atqasuk. Thus low clouds occurring with onshore flows at Barrow might be expected to be thinner or dissipate altogether at a more inland location such as Atqasuk. The effect would presumably be weaker for higher clouds, as indeed seems to be the case. The effect would also be smaller earlier in the summer when the ocean is still largely frozen and less likely to be a source of moisture and clouds during onshore flow. This is consistent with the results shown in Table 1. What is not clear is why a wet "bias" can also be found at Barrow for flows other than onshore or why higher clouds at Atqasuk appear to have larger LWPs than Barrow for winds in the 0° to 45° range, which are also onshore.

[23] The variations of the cloud LWPs and their site-to-site differences can be substantial and depend on month, cloud base height, and wind direction. There is an overall similarity in the LWP distributions at Barrow and Atqasuk for the full June–September 1999 period that can be seen in the last row of Table 1, but this is somewhat deceptive and evidently results from a combination of compensating elements including temporal trends, the direction of fetch, the base height of the clouds, and possibly other factors not considered here. The observed behavior is consistent with our hypothesis that air-surface interactions may play a role in determining the spatially evolving characteristics of clouds at the North Slope. Pending a more detailed modeling and analysis study of surface effects, however, the evidence is not conclusive, and in any event, air-surface interactions are unlikely to be a dominant factor in many cases. In principle, it is possible to further subdivide cloud properties according to various combinations of wind speed, direction, cloud base height, month, etc., but the number of cases in each category then becomes small, and the significance of any particular result is doubtful. When data from several years have been collected, such an approach should be more informative.

5. Comparisons With ECMWF Model

[24] The ECMWF model is a global spectral model. The operational version at the time of the comparison used a spectral resolution of T_L319, with an equivalent linear grid of about 60 km spacing, and a vertical grid of 31 model layers, of which seven are located in the lowest 2 km. Data from the model grid points closest to Barrow and Atqasuk, centered on 71.05°N, 156.8°W and 70.48°N, 157.5°W, respectively, were used for the comparison. Both of these are treated as land points in the model.

[25] The treatment of clouds in the ECMWF model is based on the prognostic cloud scheme developed by *Tiedtke* [1993] with some modifications described by *Jakob* [1994] and *Gregory et al.* [2000]. Model clouds are simulated by two prognostic equations for cloud condensate and cloud fraction, respectively. Cloud generation and dissipation are linked to the large-scale flow and other model parameterizations such as convection, radiation, and turbulence. Only one prognostic equation for condensate is solved, while the phase of the condensate is determined solely as a function of temperature; pure water clouds are assumed to exist above 273 K, pure ice clouds below 250 K, and mixed phase clouds in the range of 250 K to 273 K.

[26] To assess the ECMWF model's ability to simulate clouds in the Barrow-Atqasuk region, output from the operational model forecasts was analyzed at 1-hour intervals. In order to avoid model spin-up problems while still ensuring a good representation of the large-scale flow, consecutive 12- to 35-hour forecasts were used to produce a continuous time series of the required model quantities. This technique has been successfully applied in previous comparisons of the ECMWF model with data [e.g., *Mace et al.*, 1998; *Beesley et al.*, 2000].

[27] We began with a comparison of the modeled and measured (from twice per day soundings) monthly mean profiles of temperature and relative humidity at Barrow to see how well the model simulated the ambient environmental conditions in which clouds develop. Figure 7 shows the results by month. The agreement between the measured and predicted temperatures is good, but the predicted relative humidity tends to be somewhat low between approximately 1 and 5 km for June through August. Humidities are not especially high in this height range, however, and observations showed that most of the clouds formed at lower levels. The agreement below 1 km is quite good, but even at this level, there is a slight tendency to underpredict the humidity as well. The humidities at these low altitudes are also relatively high (~70% or more), and a slight underprediction here might be more important in reducing the likelihood of cloud formation.

[28] We computed the LWP in the model by vertically integrating the average liquid water content for each level in the model above the selected grid cell. For comparisons with data this is preferable to integrating only over the cloudy portion of each grid cell because the hourly MWR data are averages over both clear and cloudy portions of the sky. Table 2 shows a comparison of the simulated and observed LWPs at Barrow and Atqasuk by month and for the whole study period. Overall, the model only produces about 56% of the observed median LWP at each site. The model does somewhat better in producing the observed LWP values in July and August, and, in the case of Atqasuk, in September as well.

[29] A comparison of the measured and modeled median LWPs at Barrow and Atqasuk as a function of cloud base height interval is shown in Figure 8. In Figure 8 we have used four height intervals, each accounting for approximately 25% of the observed values: 0–125 m, 125–350 m, 350–1000 m, and >1000 m. The median height in each interval is used to determine the horizontal location of each point in Figure 8. It is apparent that the ECMWF model consistently underpredicts the observed values regardless of cloud height. The model also misses the relatively large differences in median LWP values at Barrow and Atqasuk for the lower categories of cloud base heights but does better for the two higher classes.

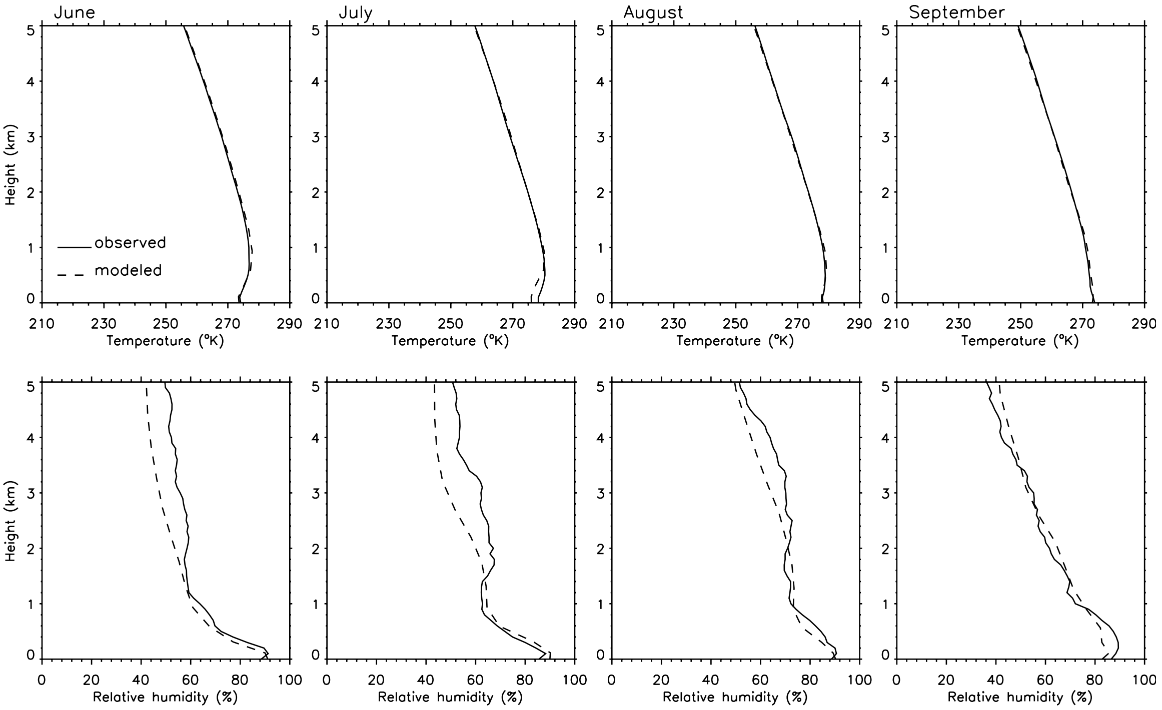

Figure 7. Comparison of monthly mean profiles of temperature (top) and relative humidity (bottom) from the European Center for Medium-Range Weather Forecasts model and the soundings at Barrow.

[30] The underprediction of LWPs is consistent with the dry bias in the relative humidity profiles shown in Figure 7, but it seems unlikely that the bias alone is the source of the underprediction. If it were, one might expect the greatest discrepancies in the LWPs to occur for clouds with the highest bases where the dry bias is larger, but Figure 8 shows that the model actually performs somewhat better for those cases. This suggests that some other aspect of the cloud parameterization scheme leads to underpredictions of LWPs.

[31] We have also compared the simulated and observed LWP values at Barrow and Atqasuk as a function of wind direction (not shown) when the ceilometer indicated the presence of clouds at Barrow. The performance of the model is mixed. The model underpredicts the observed values for almost every direction sector for both high and low clouds. Despite this, it does reproduce the pronounced maxima in the Atqasuk LWPs at 180° to 225° for low clouds and at 0° to 45° for high clouds (cf. Figure 6). The model often shows little difference in the LWP values between the two sites, however, and when it does, it shows little skill in reproducing the sign of the differences.

Table 2. Median Observed and Modeled LWPs at Barrow and Atqasuk

Period	Barrow		Atqasuk	
	Observed, mm	Modeled, mm	Observed, mm	Modeled, mm
June	0.013	0.005	0.033	0.004
July	0.028	0.017	0.023	0.018
August	0.050	0.030	0.047	0.029
September	0.050	0.025	0.043	0.035
June–September	0.034	0.019	0.036	0.020

[32] A model bias in the predicted shortwave radiation was also found that is consistent with the biases found for LWP. Figure 9 shows plots of the observed and modeled LWP and incoming shortwave radiation measured by an Eppley Precision Spectral Pyranometer as a function of time at Barrow. The thin lines are daily averages for the hours when the sun is above the horizon; the bold lines are 15-day running means. The model usually captures the occurrence of cloudy periods, as can be seen from the corresponding peaks in the daily LWP values in the top panel, but the underprediction of the LWP values is also evident, as is the related overprediction of the shortwave radiation. Similar

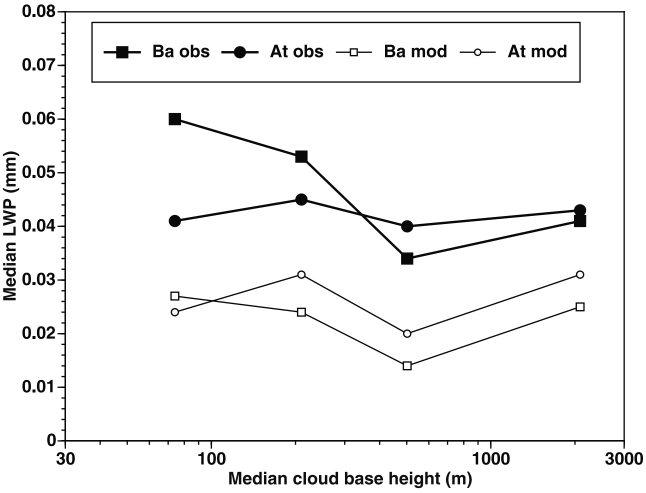

Figure 8. Comparison of the measured and modeled dependence of median LWPs at Barrow and Atqasuk as a function of cloud base height.

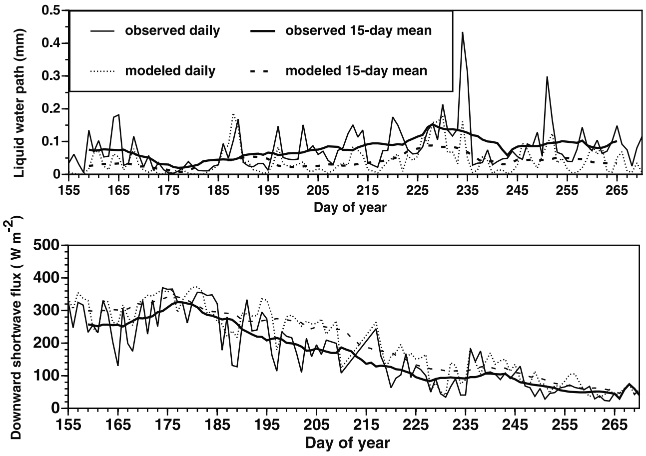

Figure 9. Comparisons of observed and modeled daily and 15-day running means of LWP (top) and downward shortwave radiation (bottom) at Barrow.

radiation data were not available at Atqasuk in 1999, so an equivalent comparison cannot be made there.

[33] The parameterization of clouds in numerical models is a difficult problem, and adequate descriptions of arctic clouds are particularly challenging. An evaluation of the parameterization schemes in the ECMWF model and the improvements that seem to be required by the comparisons shown here is beyond the scope of this paper, but we can make several comments.

[34] First, the observed differences in the cloud properties between Barrow and Atqasuk appear to be significant but can be somewhat subtle. Given the general underprediction of LWPs by the model, the relatively coarse grid spacing (~60 km) compared with the distance between Barrow and Atqasuk (~100 km), and the fact that the two grid points under consideration are adjacent to each other, it is not surprising that the model does not capture these differences with any particular skill. The grid increment of the operational ECMWF model has recently been improved to approximately 40 km, which will provide additional grid points over which the boundary layer can adjust as winds blow onshore from the ocean over land. It will be interesting to use future data sets of the kind discussed here to determine whether the model's performance is improved by this feature.

[35] Second, analyses of SHEBA data [*Beesley et al.*, 2000] have shown a similar underprediction of LWP values over the ocean and ice by the model so that at least some aspects of this problem are more generic and not related to any particular feature of the region around the NSA/AAO CART. As noted earlier, the model produces mixed phase clouds for temperatures between 250 K and 273 K. If the amount of ice produced is too large, then the water content will be too low. *Beesley et al.* [2000] found that the ECMWF model produced too much ice in clouds over the SHEBA site even when the actual clouds had substantial water content. We have examined the mean liquid water and ice water profiles at Barrow simulated by the model for each month. In general, the ice water content is much lower than the liquid water content in the lowest few kilometers, so that even if all of the ice there were converted to water, there would still be a marked low bias in the model values of LWP. The picture is complicated, however, by the fact that ice falls out of the cloud fairly readily and thus may not contribute much to the mean ice water profile.

[36] Third, the model point closest to the location of Barrow is treated as a land point, which can be a problem whenever one is dealing with a coastal environment. The low bias in the simulated LWP values described above might conceivably be less if conditions at Barrow were represented by a model grid point over the ocean. To assess this possibility, we have also examined the model output from an adjacent grid point located over the ocean just to the north of Barrow. The results were generally similar to those found for the land point, and for some wind directions the ocean point actually gave slightly lower median LWPs. Thus the low LWP bias does not seem to be caused by the choice of a nonrepresentative grid point. We also looked at the model output for an inland grid point just to the south of Atqasuk. That point gives somewhat lower values of median LWP for southeast winds than was found for the grid point closer to Atqasuk but similar or higher values for all other directions. For the June–September time period and for all wind directions the median LWP at this inland point was 22% higher than that at the Atqasuk grid point but still well below the observed value at Atqasuk.

[37] Finally, the vertical resolution in the ECMWF model may also have been a problem. The lower layer heights for the model used for the 1999 simulations were approximately 30, 150, 350, 630, 975, 1400, 1800, and 2200 m. For thin stratus clouds this spacing may be inadequate. Beginning in October 1999, the planetary boundary layer resolution in the model was doubled so that future comparisons of the type described here will provide a useful test of the effects of vertical resolution.

6. Summary and Conclusions

[38] We have compared liquid water paths of arctic clouds at a coastal site and an inland site at the North Slope of Alaska using MWR measurements at Barrow and Atqasuk, respectively, during the period June–September 1999. We have also compared the data with the corresponding values determined from the ECMWF model to evaluate the model's ability to simulate the observed LWPs as well as any site-to-site differences in them. Our principal findings are as follows:

1. Barrow LWP values were much lower than those at Atqasuk in June but were somewhat higher in the later months as the LWPs increased at both sites.
2. For winds from the more common onshore wind directions, the cloud bases at Barrow are much lower than for winds from other directions.
3. There is a complex dependence of median LWPs on wind direction and cloud base height. The median LWPs for low clouds (cloud bases <350 m) and onshore flows were larger at Barrow than at Atqasuk; for higher clouds the Atqasuk values were somewhat higher than at Barrow, but those differences were usually small.
4. The dependence of the relative cloud characteristics at Barrow and Atqasuk on wind direction and cloud base height suggests that surface conditions may play an

important role in determining those characteristics, but the evidence is not yet conclusive.

5. The ECMWF model has a small dry bias in the relative humidity in the lowest 1 km for most of the summer and a somewhat larger dry bias between 1 and 5 km.

6. The model underpredicts the values of the LWP at both sites for most circumstances, and it is generally unsuccessful in simulating the relative differences in the cloud LWPs at the two sites.

7. The systematic underprediction of LWPs by the ECMWF model and its limited ability to reproduce the differences in LWPs at the two sites indicate that, with the parameterizations and resolution used, it is not a sufficiently precise tool to study the reasons for such differences.

8. It seems unlikely that the dry bias in the relative humidity shown by the model is solely responsible for the underprediction of LWP values. The calculation of ice-water ratios in mixed phase clouds may also be a problem.

9. A high bias in the predicted shortwave radiation was found that is consistent with the low bias found for LWP.

10. An adjacent ocean grid point does not appear to be more representative of conditions at Barrow than the land grid point in which Barrow is located; that is, the low bias in the LWP values are similar at the two sites. A grid point somewhat farther inland than Atqasuk gives a smaller bias in the LWP predictions compared with the grid point at Atqasuk, but its values are still too low.

[39] Although our results thus far are intriguing, we believe that a more complete and statistically robust picture of the cloud properties at Barrow and Atqasuk will emerge with the simultaneous collection of MWR, rotating shadowband radiometer, and ceilometer data at both Barrow and Atqasuk for three or more warm seasons. Logistical and instrumental problems have precluded this thus far, but such data began to be collected in the summer of 2001. These data will allow the comparison of cloud optical depths and effective droplet radii in addition to LWP values at the two sites, and will provide additional information against which models such as that from the ECMWF can be evaluated.

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J. C. Doran and S. Zhong, Pacific Northwest National Laboratory, P.O. Box 999, 902 Battelle Blvd., Richland, WA 99352, USA. (christopher.doran@pnl.gov; s.zhong@pnl.gov)

C. Jakob, Bureau of Meteorology Research Centre, 150 Lonsdale Street, GPO Box 1289K, Melbourne, VIC 3001, Australia. (c.jakob@bom.gov.au)

J. C. Liljegren, Argonne National Laboratory, 9700 South Cass Avenue, Bldg 203-CE111, Argonne, IL 60439, USA. (c_liljegren@pnl.gov)