Climatology

METEOROLOGICAL CONDITIONS CONDUCIVE TO THE FORMATION OF STRATUS CLOUDS OVER THE BEAUFORT SEA

by

Kolf Jayaweera (1)
Geophysical Institute, University of Alaska
Fairbanks, AK 99701

ABSTRACT

The stratus clouds that occur over the Arctic Ocean during the summer can be separated into two categories. The first type is a thin low level cloud which is highly localized and occurs predominantly near the coast. The occurrence near the coast is due to the advection of moisture from the open leads in the sea ice by the summer sea breeze. The second type is extensive and can be very thick. This type is formed by the advection of moisture from the south. The cloud cover amount is strongly related to the direction of the 700 mb flow. A southerly flow anomaly gives rise to an increase in the amount and a northerly anomaly to a decrease.

We speculate that the observed layering phenomenon of the Arctic stratus clouds is due to the concurrent existence of these two types of clouds.

I. INTRODUCTION

A striking feature of the climate of the Arctic region is the persistence of extensive layers of stratified clouds over that area during the summer. These clouds include ground fog, thin low level stratus clouds of limited extent, extensive stratus clouds with well defined bases and tops, and occasional stratocumulus. The presence of such clouds affect the heat balance of the Arctic considerably. Because of this reason some efforts have been made to model the radiative (2) and dynamic nature (3) of these stratus cloud layers.

In the coastal region low level clouds are often reported. They are thin (300 m thick) and are extremely localized. Over the Arctic Ocean a second type of stratus cloud occurs. They are rather extensive and can extend to several hundreds of kilometers horizontally.

Although we find very few reports on observations of Arctic stratus clouds, the available information suggests that the stratus clouds can be classified into these two categories. (We should mention here that a third type 'Arctic Sea Smoke' exists; however this is strictly ground fog and occurs close to open leads in the pack ice.) In the past, either in meteorological reports or in the compilation of climatological data no distinction was made between the two types of stratus clouds. In this paper we make a distinction because we believe that for a proper understanding of the mechanism of formation of stratus clouds in the Arctic, a distinction of the two types is necessary. The first type, referred to in this paper as type I stratus occurs in a localized area, especially near the coast. The moisture sources for them are the open leads, and the clouds are formed when this moisture is advected by the summer sea breeze. Because of this sea breeze, the prevalent wind direction for the formation of this type of cloud is onshore or northerly along the (Beaufort Sea) coast.

The second type referred to as the type II stratus is the thicker, more extensive of the Arctic stratus clouds. Their tops may extend to as high as 2000 m. These clouds may occur over the entire Arctic Ocean and are formed by the moisture advection over large distances. We shall show in this paper that the formation of this type of cloud is related to the 700 mb air flow. We shall also show that a southerly anomaly of the 700 mb flow is associated with an increase in cloud cover while a northerly anomaly corresponds to a decrease.

2. PREVIOUS STUDIES

The available information on the climatology of cloud cover on the North American Arctic was initiated with the U.S. Air Force "Ptarmigan" weather reconnaissance flights from 1956-1974. These flights were made from Fairbanks to the North Pole at the 500 mb level (4). Using data from these flights, analyzed by Henderson (5), and combining them with surface observations, Huschke (6) and Vowinckel and Orvig (7) showed that the amount of cloudiness and frequency of occurrence are essentially a step function of time. The cloud cover amount increased dramatically from less that 2/10 to 7/10 between April and May and decreased back to 2/10 between September and November. These studies also showed that the increase of cloudiness in summer is primarily due to the presence of stratus clouds.

Henderson's analysis and Huschke's cloud distribution model are of particular interest to our study. They derived their cloud cover amounts from aircraft and ground observation, hence most likely refer to the thick extensive cloud cover - type II. Henderson (5) compared a large number of ground based observations over Pt. Barrow and Barter Island and made several averages of the vertical position and thicknesses of aerially observed clouds. However, her analysis was confined to an eighteen month period.

Huschke (6) attempted to obtain a cloud climatology by calibrating the ground observation with available aircraft data. Although his results excluded the Beaufort Sea area, the model Huschke used to obtain the cloud cover describes a usable technique for interpreting surface observations. Although with this model it is still difficult to obtain clear-cut cloud amounts for type II stratus clouds because of the presence of surface fogs and type I clouds, Huschke's values can generally be regarded as a good representation for the cloud amounts of type II clouds over the Arctic Ocean.

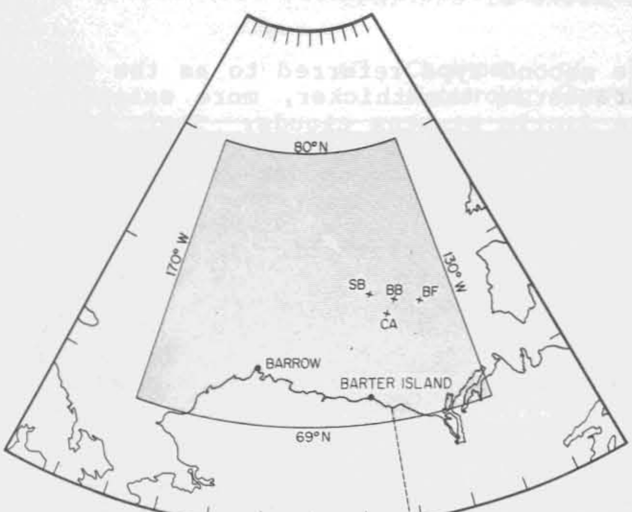

Figure 1. The study area showing the locations of surface observations Barrow, Barter Island, and Big Bear (B. B.); and the area investigated with satellite imagery (shaded).

3. FORMATION MECHANISM

The formation mechanism for the arctic fog and type I cloud is fairly clear. From the techniques used for forecasting these types of clouds and from the extensive analysis of surface synoptic patterns by Moritz (8) we can infer that the moisture for these clouds comes from open leads. The sea breeze that occurs in the coastal areas brings this moisture toward the coast to form type I clouds. The ocean-land temperature contrast in the summer leads to a sea breeze. Kozo (9) has shown that this sea breeze can be felt as far as 60 km from the shore. The presence of this sea breeze adds a northeast component to the surface geostrophic flow at Barrow and a northerly component at Barter Island. The turning of wind direction due to the sea breeze could be as much as 120^o counter clockwise. Because of this northerly component, the occurrence of type I clouds is related to a northerly air flow at the surface level.

On the other hand we can only speculate on the mechanism and meteorological situations for the formation of type II clouds. The present belief (10) is that these clouds are formed from large scale descending motion rather than from updrafts or rising motion. Herman and Goody (3) suggested that condensation is induced in initially continental polar air as it flows over the pack ice. The air cools by diffusive cooling to the colder pack ice and long wave emission to space. Once the cloud is formed intense mixing takes place by the strong cooling at the cloud top by radiative emission. Herman and Goody attributed the layered structure of these arctic stratus clouds observed by Jayaweera and Ohtake (11) to a 'greenhouse' mechanism whereby solar radiation penetrates to the interior of the cloud and causes evaporation there.

Whether clouds can form by transfer of heat and moisture downwards to a colder surface is controversial. Existence of such descending motion leading to stratus cloud formation elsewhere has been reported by Von Flicker (12) for the eastern Atlantic and by Riehl et al(13), Neiburger (14), and Neiburger et al (15) for the eastern north Pacific. However, the physical mechanism for condensation by downward motion through an inversion to a cold ice surface is difficult to understand. The cold surface should act as a sink to water vapor, hence condensation may occur, if at all, just above or in contact with the ice and surface.

The reason why the descending motion concept is preferred may be because no attempt has been made so far to distinguish between the type I and type II clouds. The type I, which predominates in surface observations, is directly related to northerly flow at ground level. A method to relate a northerly flow coming over the pack ice to the formation of clouds can only lead to a descending motion concept. If we separate the two types we can conceive another possible mechanism (16); a warm moist air mass rising over a cold

Figure 2. Daily type II stratus cloud cover for May-July 1975 and the north-south wind components at 700 mb and surface for Barrow, Alaska.

stable air mass in the Arctic and causing condensing by slow ascent. This mechanism conforms with the air motion necessary for stratus cloud formation and explains the large extent of type II cloud. A necessary condition is the availability of warm moist air. Our analysis indeed shows that type II cloud cover amount is related to the presence of southwesterly 700 mb flow.

4. DATA SOURCES AND STUDY AREA

The study area was limited to Barrow, Barter Island, AIDJEX camp, and the shaded region in the Beaufort Sea shown in Figure 1. For Barrow and Barter Island ten year (1970-79) surface observations from the National Weather Service for the summer months April through October were used. These data are the primary source of information for this study. For the shaded Beaufort Sea area we used NOAA satellite imagery for selected periods when comparisons or detailed cloud cover amounts were needed. During 1975, the operation of Arctic Ice Dynamics Joint Experiment (AIDJEX) provided us with surface observation from the Big Bear (BB) station on the pack ice in the Beaufort Sea. Those data allowed us to make detailed analysis of the cloud conditions such as daily cloud cover variations for that particular year.

Our primary data source, surface observations at Barrow and Barter Island, does not differentiate the cloud types I and II. The National Climatic Center provides this information on magnetic tape and lists three different levels of cloud. Because the occurrence of type I clouds will mask the presence of type II clouds, some criteria are necessary to eliminate the days when only type I was present. The type I clouds predominate over the higher clouds for these coastal regions.

In order to extract type II data for the cloud cover information we used the upper air radiosonde data. These data are also available on magnetic tape for the same region. The criterion was to assume that

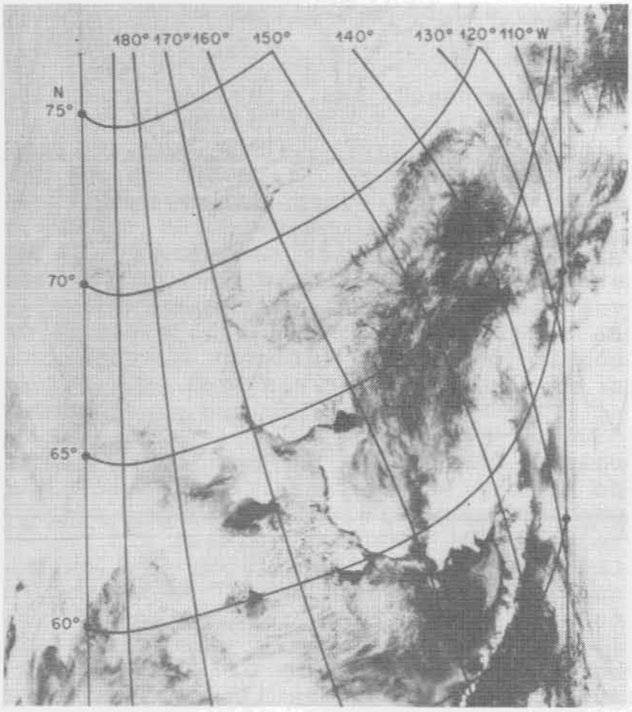

Figure 3a. NOAA-4 satellite imagery on May 8, 1975, over the study area. Visible band (0.6-0.7um), the clouds appear as indentations in the image.

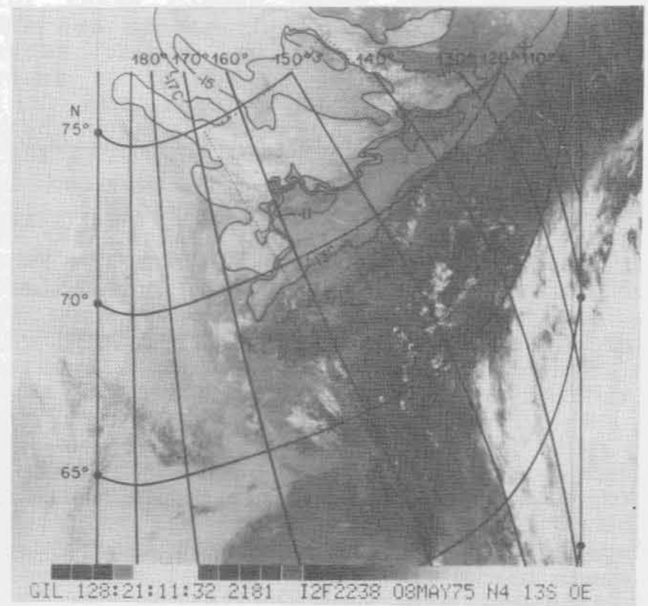

Figure 3b. NOAA-4 satellite imagery on May 8, 1975, over the study area. Infrared imagery (10.5-12.5μm), showing the radiative temperature contours in the study area. The region between the -15C and -17C isotherm correspond to stratus clouds.

type I clouds are low level phenomena with bases below 300 m and tops less than 500 m high. Kozo's analysis (9) has shown that the effect of sea breezes along the Beaufort Sea Coast can be readily felt up to about 300 m altitude. Hence we assume any cloud that forms below this level will be influenced by the sea breeze, and will most likely be a type I cloud.

For days with cloud bases above 300 m we assume that the cloud cover amount refers to type II clouds. Because both type I and II can occur concurrently we used the radiosonde humidity data as an indicator for the occurrence of type II clouds when the reported cloud bases were below 300 m. If the radiosonde showed humidities at 100% at any level between 950 mb to 700 mb (approximately 500 to 3000 m) we assumed that this is due to the presence of type II cloud. Previous investigations by the author (17) and some Soviet observations (18) have shown that stratus clouds are confined to about 2000 m above ground. Hence the use of a 700 mb upper height limit will eliminate the inclusion of middle and high clouds which in summer have cloud bases around 4000 m.

This method has several limitations. We are still limited by the cloud cover observation of the National Weather Service. These observations cannot distinguish type II clouds in the presence of the lower type I clouds. Therefore the total amount of cloud cover of the second type cannot be obtained when both types are present. The radiosonde observations are limited to a line path above the station. The occurrence of cloud along this path does not necessarily mean existence of cloud elsewhere. Similarly lack of cloud along the path does not rule out complete lack of type II clouds. In the former case, by taking the surface observed cloud cover amount we may be overestimating the amount, while in the latter case by assuming no type II clouds we may be underestimating the cloud amount. Therefore on a daily basis this method will show considerable fluctuations, as is indeed evident from Figure 2. However, using weekly or monthly mean values we believe that a reasonable estimate of the type II cloud cover amount can be obtained by this method.

In addition to the surface observations we also have access to the very high resolution imagery of the NOAA satellites. These images are available twice a day in both visible (0.6-0.7 μm) and thermal infrared (10.5-12.5 μm) bands with a resolution of 1 km. The analysis of cloud cover by these satellite images is difficult and time consuming. The technique was described in detail by Jayaweera (19). Using both the visible and infrared imagery it is possible to map the outlines of the stratus clouds over the region of interest. In Figures 3a and 3b we show examples of such complimentary images. The visible images (Figure 3a) show thick stratus clouds as indentations because of the shadows and highlights produced by these clouds on the underlying surface. The contrast in the visible imagery is very poor and as such by itself is not sufficient to detect clouds. The infrared image shows sharp contrasts in temperature between tops and the surface below. These differences may be enhanced by choosing a gray scale to cover a small appropriate temperature scale as described by Jayaweera (19). Isotherms can then be drawn as shown in Figure 3b. The cloudy area can then be outlined by superimposing the visible and infrared imagery. Sharp changes in temperature associated with highlights or shadows are assumed to be the boundary of the clouds. Although this method is tedious it has the advantage of visually recognizing clouds of type II because those of type I are too thin to be detected by this method. Therefore it automatically selects only clouds of type II.

The cloud cover amount of the area under study (shown dotted in Figure 3b) is taken as the quotient of the area covered by the cloud and the area of the region. Malberg (20) has shown that the mean cloud cover amount obtained in this way is very similar to that obtained from surface observations.

5. CLOUD COVER AMOUNT

Ten-year monthly and weekly mean cloud cover amounts were computed for Barrow and Barter Island. Very little variations were found for these two stations and the monthly mean compared well with those of Huschke's values for the Central Arctic (Figure 4). The present results are somewhat higher than Huschke but the difference is not very significant. Most importantly the step function characteristic of the cloud cover amount is evident in the present analysis.

In this figure we have also included the ten-year means by taking the raw data as available from the NWS station for Barrow to show the effect of type I clouds on the total cloud cover amount.

Comparisons of these cloud cover amounts show that in the early spring and late summer, the cloud cover amount is largely due to the type I cloud. In July, on the other hand, type I cloud, if it ever exists, occurs concurrently with the type II clouds. For the other months only a small fraction of the days does the type I occur without the type II. With this analysis it is extremely difficult to sort out the occurrence of the two cloud types simultaneously. We have noted in the past (11) that occurrence of the two layers of clouds is a common phenomenon. Therefore it is quite likely that on many occasions both types occur. It is interesting then that the occurrence of layers of Arctic stratus could be because of the presence of two types of stratus clouds, with each type formed by distinct meteorological conditions.

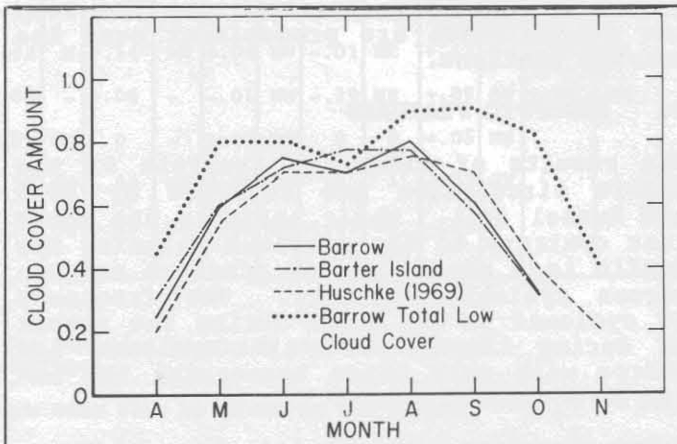

Figure 4. Ten year (1970-79) monthly mean type II cloud for Barrow and Barter Island with the results of Huschke for the central Arctic. Also the total stratus cloud cover amount for Barrow is included.

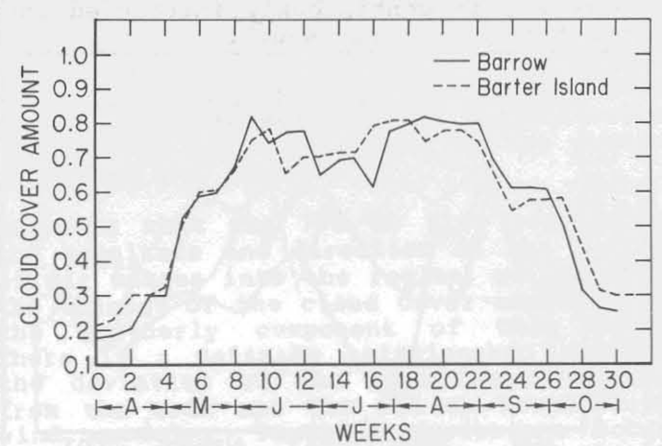

Figure 5. Ten year (1970-79) weekly mean type II stratus cloud cover amount for Barrow and Barter Island.

The weekly means over the ten-year period show only little variation (Figure 5). However, for a particular year substantial fluctuation can be seen. In Figure 6 the weekly means for 1975 are shown for Barrow, Barter Island, Big Bear, and the Beaufort Sea. The values for the coastal stations are higher but no consistent patterns or relation can be obtained for those four regions. Therefore, although over long periods the cloud cover shows a consistently high value, over short periods there is considerable variation in both space and time.

In using the data from Big Bear station no attempt was made to distinguish type I and type II clouds. Here we assumed that because of the lack of a sea breeze, type I clouds do not exist. This assumption seems to be valid because the cloud cover amounts compare very well with those derived from the satellite imagery. This supports the contention that the sea breeze is indeed responsible for the very low clouds which are predominant over the coastal stations.

6. SYNOPTIC FEATURES

The results of extensive analysis of the Arctic circulation are reported by Reed and Kunkel (21). Their analysis has shown that contrary to the previous beliefs, the Arctic is a region of low pressure and vigorous cyclonic activity. The frequency of cyclones is as large during the summer as during the winter. Anticyclones are scarce with only three traversing the basin in a typical summer.

These synoptic analyses and those of Dzerdzeevskii (22), Prik (23), and Vowinkel and Orvig (7) imply that the Arctic is a region of low pressure characterized by a well defined convergence of air into the central polar ocean. Thus a steady stream of warm air is continuously introduced into the Arctic from the south.

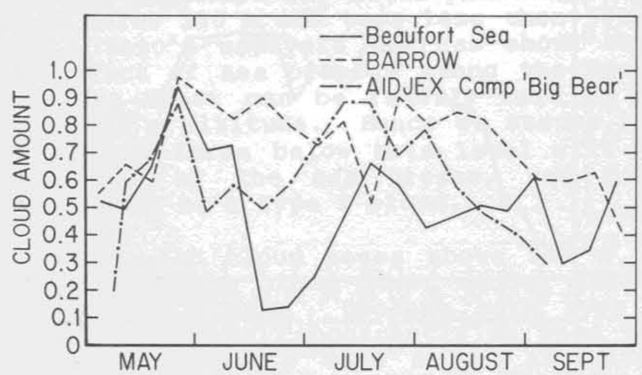

Figure 6. Weekly mean type II stratus cloud cover amount for Barrow, AIDJEX camp, and Beaufort Sea for summer of 1975. The Beaufort sea area referred to that area shaded in Figure 1 and cloud cover data is obtained from satellite data.

The existence of such convergence and wave disturbances bringing warm southerly air can be seen from the mean 700 mb flow. Starting from about April we notice that the mean 700 mb isoheights deviate from the near concentric lines typical of the winter to a southerly flow. If we consider the 700 mb flow to represent the general advection of air into a region we may conveniently assume that the occurrence of large amounts of cloudiness is related to the influx of warm southerly air into the Arctic.

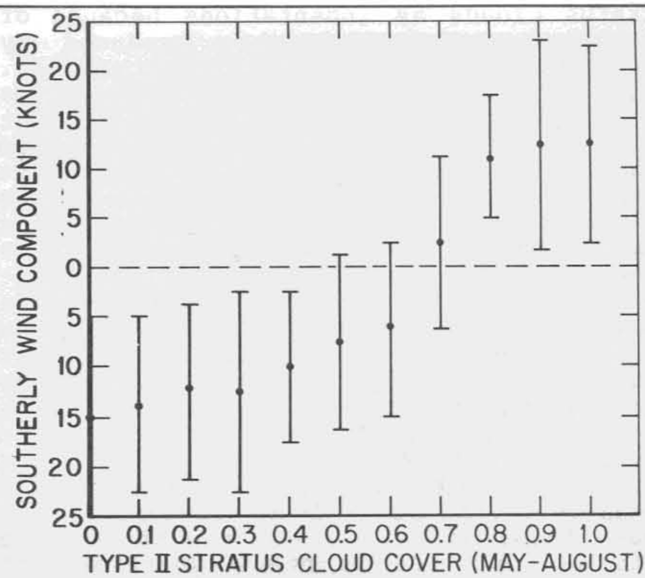

Figure 7. The relation between the type II stratus cloud cover amount and the southerly wind component at 700 mb level over Barrow. The negative values correspond to northerly component (1 knot is approx. 0.5 m sec^{-1}).

7. RELATION OF CLOUD COVER AMOUNT TO 700 MB FLOW

The earlier discussion suggests that the high cloudiness in summer may be a consequence of the general southerly flow at the 700 mb level. We will now show that fluctuations from this basic state of high cloudiness correspond to changes in the 700 mb flow.

In order to do this we compared the daily cloud cover at Barrow for selected summer periods with the north-south component of 700 mb flow. The latter was obtained from the 0000Z radiosonde sounding at Barrow (1400 local time). One such example is shown in Figure 2. The fluctuation of cloud cover with the changes in the southerly component of 700 mb is evident from this example. Decrease in the cloudiness can be seen for days when the wind direction changed to the north. Interestingly no such obvious relationship can be seen for surface winds which are also shown in Figure 2.

The effect of 700 mb flow on cloud cover can be demonstrated even more when the changes of the cloud cover amounts are compared with the 700 mb anomaly flow. We calculated these for the period 1970-79 for Barrow.

The results are shown in Table 1. The positive changes in the cloud cover represent increases in cloudiness over the ten-year mean period and the wind direction is the anomalous wind component to mean

TABLE 1

Month	1970-79 Mean cloud Cover	1970		1971		1972		1973		1974		1975		1976		1977		1978		1979	
		C	A	C	A	C	A	C	A	C	A	C	A	C	A	C	A	C	A	C	A
April	0.25	+.13	SE	+.04	SE	-.09	E	+.05	SW	-.19	N	-.11	NW	+.13	S	0	W	+.01	N	-.01	-
May	0.6	-.05	NE	+.04	SE	0	-	+.02	SE	+.04	SW	+.02	SW	+.02	E	+.05	W	-.11	N	-.05	NE
June	0.75	+.03	E	-.23	NE	-.05	-	+.02	-	+.02	W	+.14	SW	+.04	SW	-.01	NE	+.11	S	-.10	NW
July	0.71	0	-	+.01	-	-.11	NE	-.11	W	+.03	-	+.06	-	-.01	NW	-.19	NE	+.09	SW	+.06	SW
August	0.8	+.04	E	-.03	NW	-.01	-	+.06	SW	-.07	SW	0	-	-.08	NE	0	W	+.05	NW		
Sept.	0.6	+.06	-	+.05	-	+.04	N	+.02	-	-.12	NW	-.06	NW	+.04	SE	0	-	+.02	SE		
Oct.	0.35	+.03	-	-.04	W	+.08	SW	+.09	SE	-.23	N	-.11	NW	-.11	NW	+.15	SW	-.02	N		

Legend for Table 1

'C' represents the deviation of the cloud cover from the ten year mean. A positive value corresponds to an increase and the negative to a decrease.

'A' the 700 mb wind anomaly direction from the long term mean flow as given by the monthly Weather Review Summary maps.

flow. Except for very few cases, the monthly mean increases in cloud cover were always related to the southerly anomaly in the 700 mb flow, while a decrease was related to a northerly anomaly.

Our final analysis demonstrates that not only the changes in the cloud cover are related to wind but also that the actual amount of the cloud cover can be related to the magnitude of the southerly flow. To show this the daily cloud cover amount for Barrow was sorted into tenths. For each category the southerly component of the 700 mb flow was computed and averaged. The average southerly wind component is then plotted against the corresponding cloud cover amount as shown in Figure 7. The bars represent the standard deviation. Although this deviation is rather large, the results show a definite trend that high cloudiness is associated with southerly flow. Furthermore, less than 5/10 cloudiness for type II clouds over Barrow is always associated with a northerly component of the 700 mb wind.

8. CONCLUSION

The study described in this paper is based on the following hypothesis: the large cloud cover amount of stratus clouds over the Arctic Ocean is a basic meteorological phenomenon during the summer. Near the coastal regions there are two types of these clouds. The first type is a local phenomenon caused by the moisture from open leads carried along by the sea breeze. These clouds occur within about 60 km from the shore and are not more than 200 m thick with the bases below 300 m from the surface. The second type is more extensive, thicker, and the clouds are formed by the influx of warm moist air into the arctic region.

Using a simple criterion of cloud thickness and base heights we were able to differentiate, to a large extent, the two types of stratus clouds from the surface observations at Barrow and Barter Island. We find that during the months of May through August only about 10% of the cloud cover amount is due only to type I, while during early spring and fall, these clouds account for about half the total cloud cover. This means that type I cloud cover occurs over a longer period in the summer than type II.

Assuming that the 700 mb flow represents the magnitude and direction of the influx of air masses into the region, we compared the changes of the cloud cover amount with the southerly component of this flow. There is a definite relationship between the deviation of the cloud cover amount from the mean and the 700 mb North-South wind anomaly. Positive deviations occur for a southerly anomaly while a northerly anomaly gives a negative deviation. Another interesting result is that less than 5/10 cloud cover at Barrow always corresponded to a northerly 700 mb flow. We realize that the 700 mb level is higher than the heights of the stratus clouds, but it is recognized in weather analysis that this level represents advection of moisture and heat.

Our analysis on the monthly mean cloud cover amounts compared well with those of earlier work. They showed the characteristic step function pattern. However, the weekly means show some fluctuations. These fluctuations are considerable, both spatially and temporarily, when weekly means for a particular year are taken. Analysis of the cloud cover amount at the ice station in the AIDJEX network showed that type I clouds occur only very rarely or occur in conjunction with type II cloud. This may be due to the absence of the regular sea breeze that occurs near the coast.

Finally we speculate that the layering reported in the literature may be due to the occurrence of type I and II cloud simultaneously. We note here that most of the present observations of layering (11) are for regions close to the coast and we find no reports of layering deep into the Arctic Ocean.

If layering is due to the occurrence of these two types of clouds, then the mechanism of formation of the two layers is different. Hence their microphysical characteristics should be different. Also the condensation nuclei for type I clouds will be of local origin and be primarily sea salt. On the other hand condensation nuclei for type II have travelled over long distances and should be deficient in sea salt. They will contain sulphates such as ammonium sulphate. We propose to verify these contentions from the results of experiments on the microphysical, radiative, and dynamic properties of Arctic stratus clouds conducted in the summer of 1980.

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