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Variability of Summer Cloudiness in the Arctic Basin

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With 12 Figures

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Summary

The extent and thickness of clouds in the Arctic Basin varied considerably in space and time in the late springs and summers of 1977–1979. While, on the average, clouds covered two thirds or more of the basin at any one time, cloud-free episodes were particularly common from the middle of June to late July and persisted locally for several days or even weeks. The central Arctic was less cloudy than the ocean zones closer to the coast in spring, but more cloudy in summer. Most clouds were semi-transparent, allowing recognition of underlying surface features. Optically thick clouds with middle and high level tops were associated with low pressure systems and with atmospheric flows from lower latitudes at the surface and aloft. Cloud-free skies were most frequent in high pressure cells. Climate models used to assess the impact of CO_2 and other trace gases on the radiation budget in the high latitudes should account for the heterogeneity of cloud extent and thickness in the Arctic Basin.

1. Introduction

Numerical models predict that the largest climate changes due to increased CO_2 and other trace gases will occur at high latitudes. Specifically, it is expected that arctic snow and sea ice will melt earlier in summer and start growing later in fall, consequently becoming less thick during winter (Manabe and Stouffer, 1980). Thinner ice in winter should facilitate the transfer of heat from the ocean into the atmosphere and increase surface air temperatures. If the theory is correct, early signs of the CO_2 impact should appear in the Arctic through accelerated snow dissipation in the late spring and an increased rate of ice melt in summer. Due to higher evaporation, cloud cover is expected to increase.

Empirical and modeling studies suggest that within the Arctic Basin summer cloudiness has a significant effect on the surface radiation budget and, therefore, on snow and sea ice conditions (Untersteiner, 1961; Shine and Crane, 1984). However, the role of clouds in the initiation and maintenance of the snow and ice melt, and, more generally, the influence of clouds on the radiative environment of the Basin are not sufficiently known. The arctic melt season is short and any change in its timing and in the extent of the area affected has a large impact on the energy budget of the region (Marshunova and Chernigovskii, 1968).

Data on the large-scale seasonal distribution and dynamics of arctic clouds are inadequate. This is due to the sparsity of off-coast stations and to difficulties in the automated identification of clouds from satellite imagery in the presence of snow and ice (Jayaweera, 1977; Barry, 1983). As a result, earlier reports of summer arctic cloudiness present conflicting results, ranging from upwards of 90% cloud cover with little variation (Huschke, 1969; Vowinckel and Orvig, 1970; Marshunova and Chernigovskii, 1971) to highly variable mean monthly cloudiness as low as 50% (Chukanin, 1954; Jayaweera, 1977; Gorshkov, 1980). Recently, Barry et al. (1987) used satellite imagery to classify clouds in the Arctic Basin in the springs of 1979 and 1980. They found considerable geographic and interannual variability of stratiform and cumuliform cloudiness at this time of the year.

Automated cloud analyses which rely on satellite input appear to be insufficient for adequate cloud mapping in the Arctic. Difficulties arise in the shortwave as a result of similarities in the brightness of cloud tops and the sea-ice surface and because of high solar zenith angles, which result in cloud shadowing, anisotropic scattering from clouds and the surface and, for much of the year, low illumination. An automated approach to identifying clouds which uses infrared imagery has difficulties distinguishing between the surface and the tops of low level stratus, a problem of particular significance in the Arctic.

Here, an arctic-wide analysis of cloudiness from mid-May to mid-August based on a manual interpretation of satellite data is presented. Cloud cover was charted in three thickness classes at approximately three-day intervals in 1977 and 1979, and at selected intervals in 1978. In addition, estimates of cloud-top height were made from imagery for mid-month periods and the cloud charts were compared with observations of atmospheric pressure and surface melt.

2. Data

Clouds were charted from shortwave (0.4–1.1 micrometers) and infrared (8.0–13.0 micrometers) imagery from the Defense Meteorological Satellite Program (DMSP). The polar-orbiting DMSP satellites crossed the equator at local noon and were equipped with an Operational Line Scan System Sensor (OLS) having a nadir resolution of 0.6 km (Fett and Bohan, 1977). Most imagery used in this analysis was degraded to a resolution of 2.7 km. The OLS provided a near-constant image resolution with optical compensation for motion across the 3 000 km scan tract. In the shortwave, bidirectional reflectance of the earth-atmosphere system was recorded and theoretically normalized for solar illumination. However, gain changes are not smooth at the high solar zenith angles in the Arctic, which contributes to the difficulties in employing an automated procedure of cloud charting in this region.

Daily DMSP images are available in Transverse Mercator projection on ungridded positive film transparencies scaled at $1:15 \times 10^6$. The density of the processed film is linearly proportional to scene reflectivity in the shortwave. In the infrared imagery, the grey shades are proportional to temperature.

3. Procedure

Clouds were differentiated visually from snow and ice, primarily by the characteristic large-scale features of the pack ice identified in shortwave imagery. These features included:

1) Elongated leads filled with water or grey ice, contrasting with the brighter snow or older ice fields.

2) Snow-covered floes of multi-year ice separated by darker partly flooded ice or water.

3) Patchy fields of grey melting snow and/or melt-water puddles separated by bright snow and ice in pressure ridges.

Depending on the cloud optical thickness and solar angle, these features were either completely or partly obscured. In addition, certain cloud

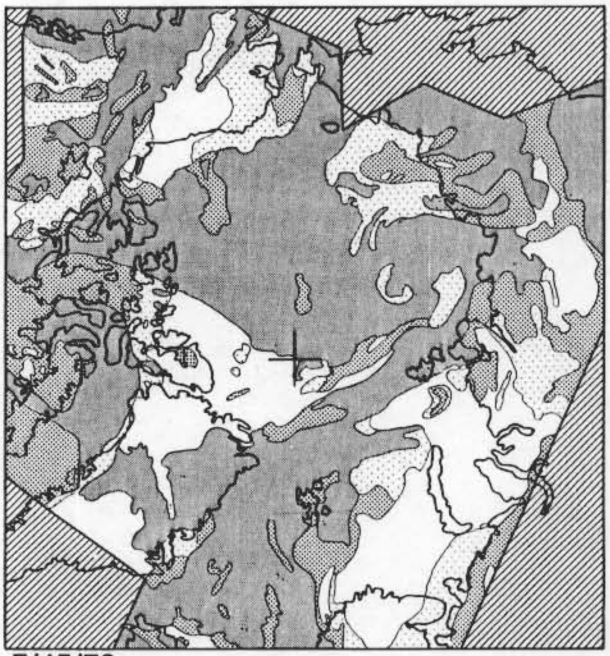

Fig. 1. Cloud-over field for July 15, 1979. Classes include: 1) cloud free (open), 2) thin clouds (light stippling), 3) moderately-thick clouds (moderate stippling) and 4) thick clouds (dense stippling). Hatched where data were unavailable. The North Pole is marked with a cross

fields, particularly those in cyclonic regions, were recognized by their characteristic shapes and patterns in both the shortwave and infrared imagery.

Charts of cloud cover, showing cloud-free skies as well as relative cloud thickness, were prepared from the DMSP transparencies (Fig. 1). Visual interpretation was assisted by an interactive analysis done on a digital image processor. The processor was primarily used to determine cloud thickness categories (cf. Robinson et al., 1983). Multiple images for a given date were combined to cover as much of the Arctic Basin as possible. Several adjacent passes, separated by as short a time interval as possible, were used to minimize the distortion due to moving clouds.

Three cloud-thickness classes and a cloud-free class were recognized.

1) Cloud free (surface features seen with high contrast).

2) Thin clouds or subresolution patchy clouds (surface features clearly recognizable but with reduced contrast as compared to cloud-free skies).

3) Moderately thick clouds or fog (surface features marginally recognizable through the cloud).

4) Thick or multilayer clouds (no surface features recognizable).

Estimates of the optical thickness of each of the three cloud classes were made, based partly on a comparison of flight data gathered in the summer of 1980 (Tsay and Jayaweera, 1984; Herman and Curry, 1984) with coincident satellite-derived cloud charts (Kukla, 1984). According to this analysis, multi-layer relatively thick cloud with a high liquid water content and with a grey optical thickness of about 25 corresponded to cloud cover class 4. Cloud charted as class 3 had a moderate liquid water content and an optical thickness of around 8 to 10. Clouds in class 2 could not be directly correlated with flight data but should have a low liquid water content and an optical thickness between 2 and 5.

Optical thickness was also estimated by measuring the contrast in DMSP image brightness between snow and open water surfaces for clear and cloudy conditions on an image processor and using the results in a detailed radiative transfer model (Robinson et al., 1983). Tentative estimates of optical thickness suggest that class 2 clouds may have optical thicknesses as low as 2; and class 4 clouds, thicknesses over 25. More coincident ground, aircraft and satellite measurements are needed to better define these optical thicknesses.

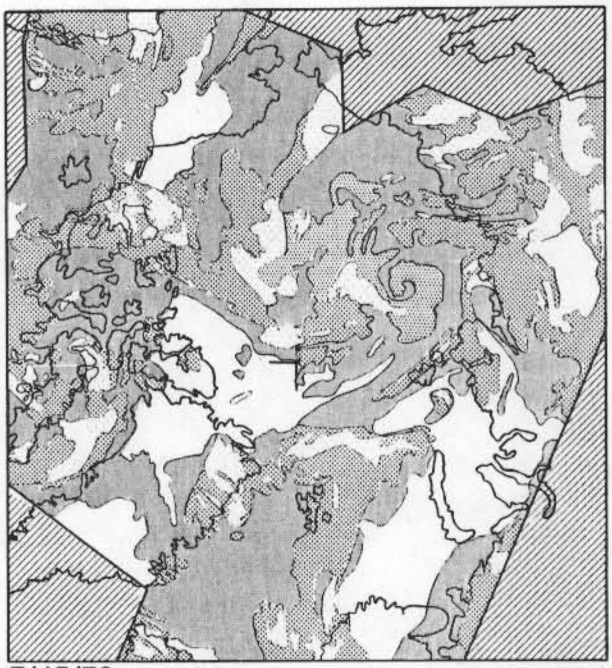

Fig. 2. Cloud-height field for July 15, 1979. Classes include: 1) cloud free (open), 2) low-level cloud tops (dense stippling), 3) middle-level tops (moderate stippling) and 4) high-level tops (light stippling). Hatched where data were unavailable

In addition to the cloud thickness charts, twelve mid-month charts showing the height of the highest cloud top were constructed for the entire Basin for the 15th of May through the 15th of August from 1977 to 1979 (Fig. 2). Cloud tops were differentiated into three relative classes, low, middle and high, relying primarily on the distinction between grey shades on infrared images and their relationship to patterns indicative of cyclonic systems. Supplementary information was obtained by examining the length of cloud shadows on the underlying pack ice or on a lower level stratus layer in the shortwave images at high solar zenith angles.

The tops of the low-level clouds were estimated to be below 1 000 m, middle-level clouds between 1 000 and 4 000 m and high-level clouds over 4 000 m. These estimates were based on in-situ measurements (Herman, 1977; Tsay and Jayaweera, 1983 and 1984; Herman and Curry, 1984) and other published sources (Reed and Kunkel, 1960; Cogley and Henderson-Sellers, 1984).

All cloud charts were digitized using the U.S. National Meteorological Center (NMC) standard data grid. Grid cells were classified according to

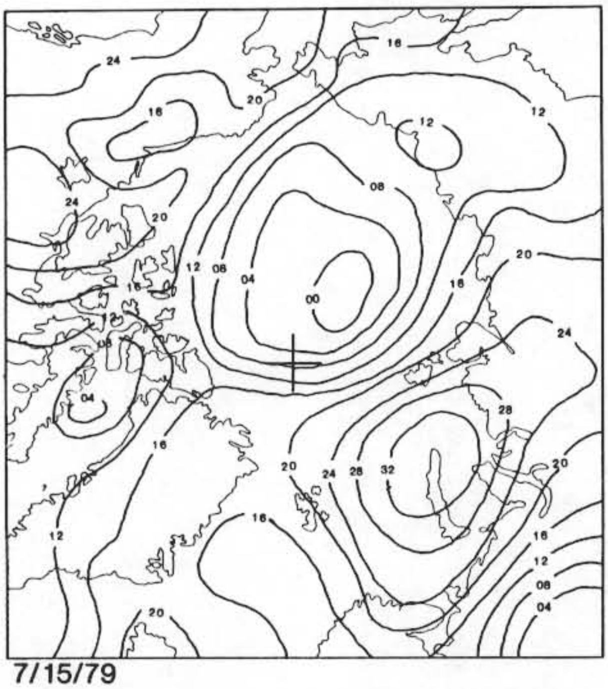

Fig. 3. Surface atmospheric pressure field for July 15, 1979 from NMC 00 Z Northern Hemisphere chart. Add 1 000 mb to all values

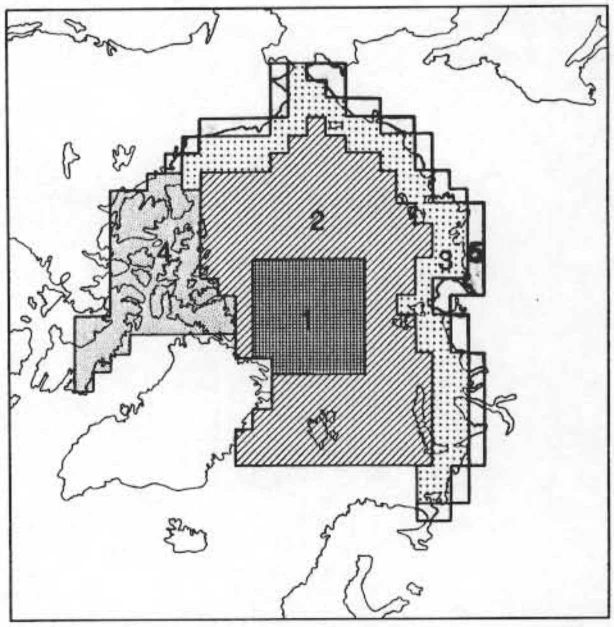

Fig. 4. Regions in the Arctic Basin used in thus study. Region 1) Central Arctic Ocean, 2) Outer Arctic Ocean, 3) Arctic Coastal Waters, 4) Canadian Archipelago and 5) Arctic Coastal Land

the most prevalent cloud or cloud-free class found in the cell unless more than half of the cell had missing data, in which case no value was assigned. NMC 00 Z surface pressure charts used in the study were digitized using the same grid (Fig. 3). The largest area within a grid cell falling between two isobars was determined and the cell assigned the average value of those two isobars. Mean-monthly 700 mb heights used in the study are from charts published in *Monthly Weather Review*.

For analysis purposes, the Arctic Basin was divided into five regions based on geographic criteria (Fig. 4). Regions contained from 35 to 146 NMC grid cells. They include the: 1) Central Arctic Ocean, 2) Outer Arctic Ocean, 3) Arctic Coastal Waters, 4) Canadian Archipelago and 5) Coastal Land. Data coverage approached 100% in the Central Arctic where satellite passes overlap the most. A similar high percentage was found for regions 2–3 in most 1978 and 1979 charts. Missing imagery resulted in region 5 in 1978 and 1979 and regions 2–4 in 1977 having between 60% and 80% cell coverage and region 5 in 1977 averaging less than 50% coverage.

Tests were conducted with two interpreters to assess the subjectivity of the charting and counting methodology. Six mid-month charts of cloud thickness were independently constructed by each analyst. Reasonable agreement was found for all charts. The average areal extent of cloud-free plus thin cloud classes for the charts differed by 8%. Individually, cloud-free regions agreed best, differing by only 2%. The largest differences were found when distinguishing between moderate and thick clouds. This is the most subjective distinction to make, particularly when distinctive surface features are absent, therefore the two classes are frequently combined in the reported results. Further information on all charting procedures may be found in Kukla (1984) and Robinson et al. (1985).

Cloud charts were prepared at approximately three-day intervals to reduce the volume of processing. While a determination of precise monthly means is not possible when sampling at this rate, the error margin is not expected to be large, given the sluggish movement of summer weather systems in the Arctic and the relatively suppressed diurnal variation of cloud cover because of the small diurnal variability of solar zenith angle. Also, since only three years were analysed, those results should not be taken as representing long-term average conditions of late spring and summer cloudiness in the Arctic.

4. Results

Significant variability in the type and spatial distribution of clouds throughout the Arctic Basin was exhibited in each of the cloud charts constructed in the 1977–1979 study interval. As an example, on July 15, 1979 thick and moderate clouds covered 65% of the Basin and were most abundant in the Outer Arctic Ocean and Canadian Archipelago (Fig. 1). Skies were clear or had thin clouds north of Greenland and in much of the Barents and Kara Seas. Considerable temporal variability in the extent of cloudiness across the Arctic Basin was also noted, as seen in the Outer Ocean (Fig. 5). Cloud cover was most extensive in early June of 1977 and 1979. Clear skies and thin clouds peaked in the second half of June and the first half of July in 1977 in all regions. In 1979, moderate and thick cloudiness also decreased between early and late June, but less so than in 1977.

Regional estimates of cloudiness for the last half of May and for all of July in 1979, based on six and ten charts respectively, are shown in Figs. 6 and 7. The zone of heavy cloudiness progressed polewards during the late spring. In May, skies were less cloudy in the Central Arctic than in either of the ocean region closer to the coast. The opposite case was observed in July 1979, when the Central Arctic was cloudiest, with clear skies pres-

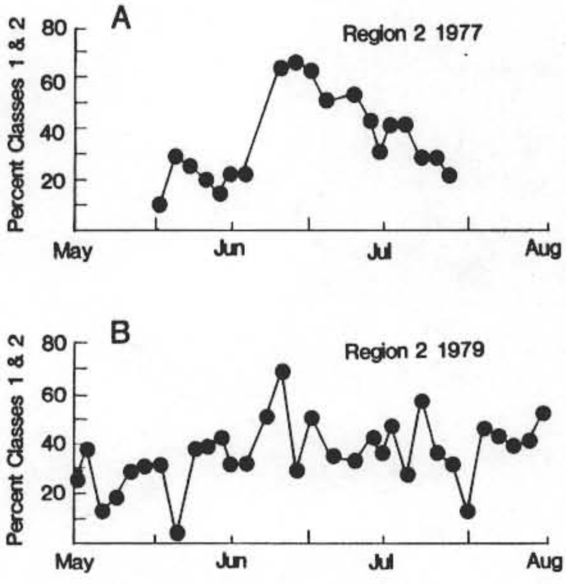

Fig. 5 a. Coverage of cloud-free skies plus thin clouds (classes 1 and 2) over the Outer Arctic Ocean (region 2) for approximately every three days in June and July 1977

Fig. 5 b. Same as a, except for May 15 to August 15, 1979

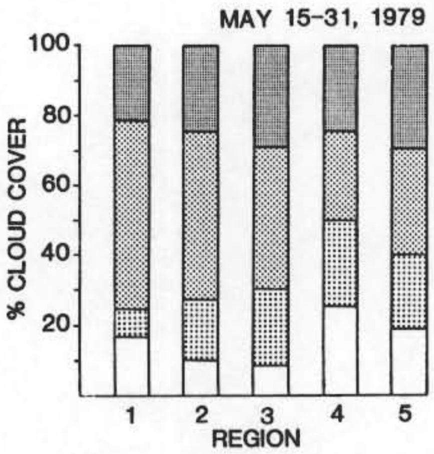

Fig. 6. Estimates of the mean area covered by the three cloud classes and the cloud-free class in the five study regions for the second half of May 1979. Symbols same as in Fig. 1

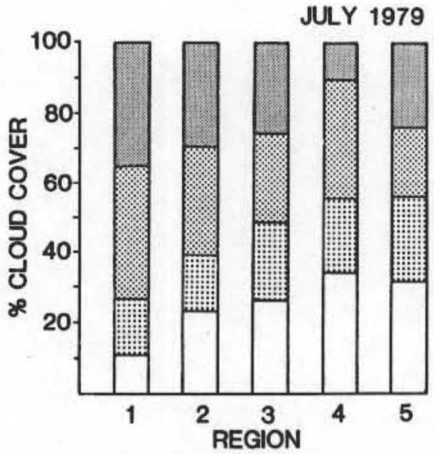

Fig. 7. Same as Fig. 7, except for all of July 1979

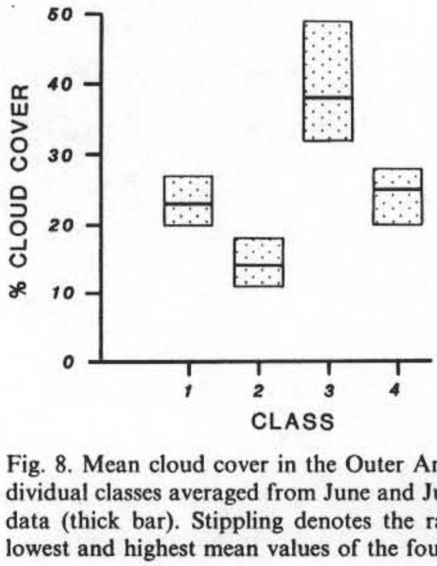

Fig. 8. Mean cloud cover in the Outer Arctic Ocean by individual classes averaged from June and July 1977 and 1979 data (thick bar). Stippling denotes the range between the lowest and highest mean values of the four months

ent approximately 10% of the time. Cloudiness decreased towards the coast, where coastal regions and the Archipelago had approximately 50% moderate and thick cloud cover. The July 1979 results are representative of estimates for July 1977 and June 1977 and 1979. For instance, in the Outer Ocean, monthly means for the four months only differed by an amount between 6% for thin clouds and 16% for moderate clouds (Fig. 8).

The distribution of cloudiness in the Basin was compared with coincident surface pressure data and an association between increased cloudiness and lower pressure was found. On a daily basis, clouds, particularly the moderate and thick varieties, were closely associated with the position of surface lows (Fig. 3). Several vigorous lows penetrating into the Basin in the first half of June 1979 (e.g. Fig. 9) resulted in the extensive cloud cover previously mentioned. Likewise, cloud-free skies were most frequently associated with high pressure cells. The optically thick clouds were also associated with atmospheric flow from lower latitudes at the surface and aloft. These relationships are apparent when examining estimated monthly

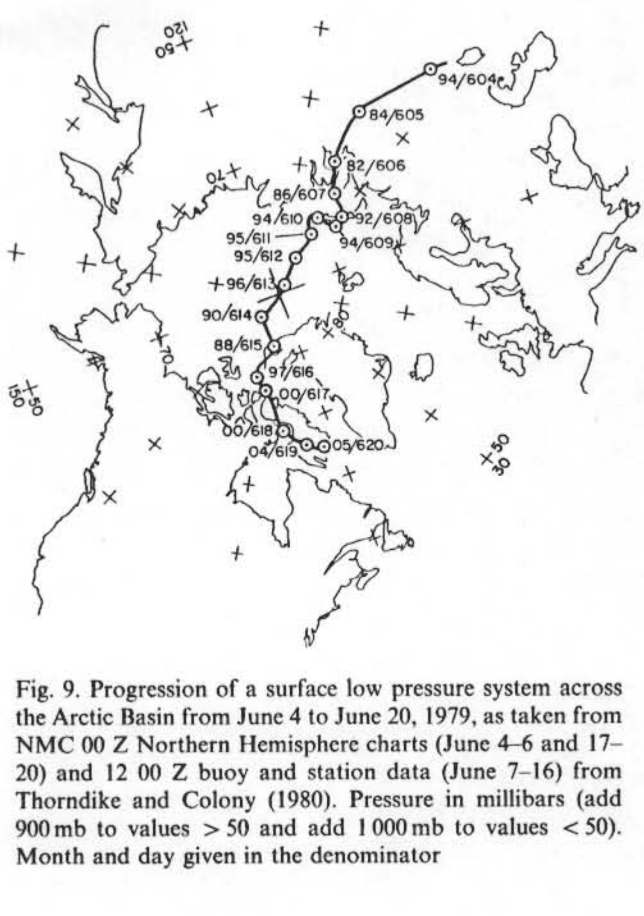

Fig. 9. Progression of a surface low pressure system across the Arctic Basin from June 4 to June 20, 1979, as taken from NMC 00 Z Northern Hemisphere charts (June 4–6 and 17–20) and 12 00 Z buoy and station data (June 7–16) from Thorndike and Colony (1980). Pressure in millibars (add 900 mb to values > 50 and add 1 000 mb to values < 50). Month and day given in the denominator

A

B

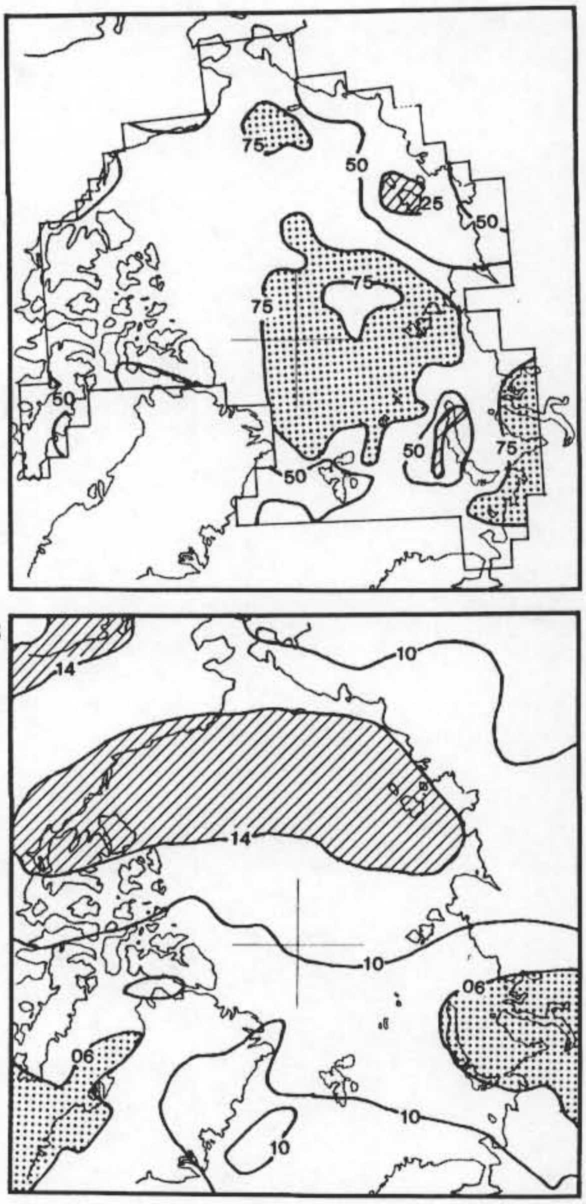

Fig. 10 a). Percent frequency of moderate and thick cloud cover for June 1979 within the study regions. Areas with > 75% cover shown with stippling, < 25% cover with hatching

Fig. 10 b). Mean-monthly surface pressure field for June 1979. Derived from NMC charts on dates when clouds were charted. Add 1 000 mb to all values

means of cloudiness and surface pressure. Figure 10 shows the heaviest cloud cover in June 1979 between a high in the Beaufort-East Siberian Sea and a zone of lower pressure extending from north of Greenland into the Kara Sea. Here, winds, also verified at the 700 mb level, tended to flow from

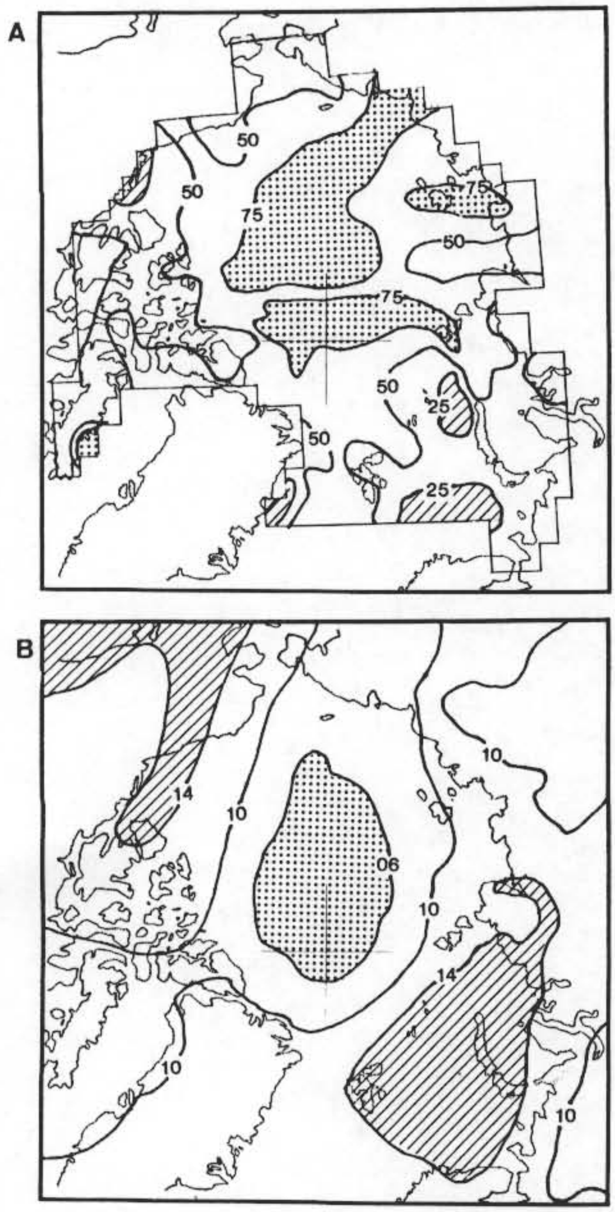

Fig. 11. Same as Fig. 10 except for July 1979

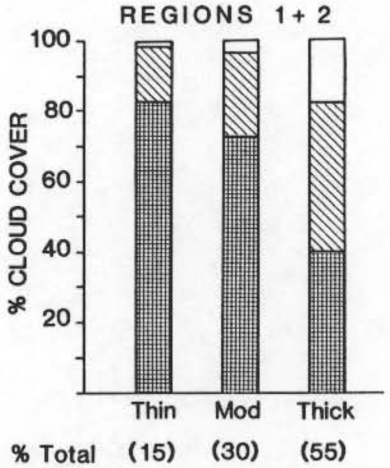

Fig. 12. Percentage of total clouds with low (squares), middle (hatching) and high (open) tops within each thickness class for the Central and Outer Arctic Ocean regions from an average of mid-month charts for May–August 1977–1979. Percent totals at the bottom of the figure show the percentage of the cloud-covered portion of the regions having clouds of a given thickness class

the south during the month. Figure 11 shows an abundance of clouds over a low in the Beaufort-East Siberian Sea region and relatively cloud-free skies over a Kara and Barents Sea high in July 1979.

The majority of clouds throughout the Arctic Basin had cloud tops at the low or middle level (Fig. 2). Clouds with middle and high tops were mostly in regions of low pressure and along fronts associated with the lows. No seasonal or inter-annual differences were noted in this tendency or in relationships between cloud-top height and cloud thickness. Over ocean areas, 70% of the moderately thick clouds were low (e.g. Fig. 12). Over the Coastal Land region, 60% of the moderately thick clouds were low, while 45% were of this height over the Archipelago. Over ocean regions, approximately equal amounts of thick clouds with middle and low tops occurred, while fewer clouds had high tops. Middle-level thick clouds dominated the Coastal Land and Archipelago regions. High-thick clouds were noted just as frequently as low-thick clouds over the Coastal Land region.

5. Discussion and Conclusions

These observations of the heterogeneous nature of cloudiness over the Arctic Basin in space and time during the late springs and summers between 1977 and 1979 agree with the basin-wide results of Barry et al. (1987) for the springs of 1979 and 1980 and those of Jayaweera (1977) for the Beaufort Sea in June and July 1975. The late-spring cloud maximum in 1977 and 1979, which occurred over all but the central portion of the Basin, and the later retreat of the maximum to the Central Arctic region further supports the suggestion that extensive spring cloudiness is associated with the advection of moisture from lower latitudes by synoptic disturbances (Barry et al., 1987). Others have also addressed the positive relationship between warm advection and increased cloudiness in the Basin (e.g. Reed and Kunkel, 1960; Jayaweera, 1982).

The initiation of snow melt on the pack ice appears to accompany the regional cloud maximum (Robinson et al., 1986 and 1987). Melt does not appear to preceed the increase in cloudiness, thus ruling out a local moisture source as a major contributor towards early cloud development. Warm air accompanying the clouds into the Basin may initiate the melt; however, the clouds more than likely enhance the melt by increasing the infrared irradiation at the surface. This results in an increase in the net radiation over high-albedo surfaces (Ambach, 1974; Cogley and Henderson-Sellers, 1984).

As the majority of clouds over the Basin were relatively transparent, they should have allowed a high amount of incoming solar radiation to penetrate to the surface. If this is a common feature in most years, it may have important implications in terms of the earth/atmosphere energy budget and the role of summer arctic cloudiness in any future climatic change.

Further monitoring of arctic cloudiness should serve as a means for recognizing potential climatic changes in the high latitudes. Climate models used to assess the impact of CO_2 and other trace gases on the radiation budget in the high latitudes should account for the heterogeneity of cloud extent and thickness in the Arctic Basin.

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