BIOGRAPHICAL SKETCH

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REMOTE SENSING OF SEA ICE FROM EARTH SATELLITES

E. Paul McClain

1. Introduction

There are economic and scientific requirements for monitoring polar ice fields, including ice that develops on large subpolar lakes such as our own Great Lakes. Comprehensive and repetitive ice surveys by means of ground parties or by aircraft are hazardous, time-consuming, and prohibitively expensive in the vast, harsh, and poorly accessible regions at high latitudes. A polar-orbiting Earth satellite, however, is a practical means of obtaining much useful sea ice information for operational and research purposes.

Knowledge of sea ice distribution and condition, particularly during periods of formation and breakup, is vital to commerical and military ship movements in the Arctic and Antarctic. More complete and systematic knowledge of the processes of ice buildup, movement, deformation, and decay is needed for the development of analysis and forecasting techniques and effective planning and management of sea transport in polar oceans.

There exists a strong, but not completely known or understood, two-way coupling between the atmosphere and ocean that involves the effects of changing ice fields. This inter-relationship is important in short-period as well as extended atmospheric, hydrologic, and oceanic forecasting. Ice cover, especially the leads and other openings, also plays an important part in the heat balance of polar regions, and this in turn influences atmospheric and oceanic circulation on all scales from local to the general circulation.

The potential of meteorological satellite data for mapping ice fields was quickly recognized after the first pictures from TIROS experimental satellites became available. After the satellite system became fully operational in 1966, and when many countries began receiving their own pictures from the Automatic Picture Transmission (APT) camera system, ice reconnaissance with the aid of satellite pictures became increasingly widespread by the United States, Canada, and other countries with interests at high latitudes. The USSR is also making use of its own and U.S. satellite data for sea ice surveys.

2. Use of Meteorological Satellite Data for Sea Ice Mapping

The first of a new generation of Improved TIROS Operational Satellites (ITOS) was placed in orbit 1460 km above Earth last winter. These new NOAA spacecraft combine the global coverage and local readout capabilities, formerly requiring two satellites, in a single satellite. In addition to the television cameras, ITOS-1 carries a two-channel scanning radiometer, one channel detecting visible radiation and the other infrared radiation. Figure 1 is an example of polar ice as it appears in an APT (Automatic Picture Transmission) picture taken by ITOS-1 over the northeast Canada area. APT pictures can be obtained by anyone in the world using relatively inexpensive receiving equipment, and there are now over 500 such local readout stations in over 50 countries.

Although cloud covers much of the Davis Strait in figure 1, first-year pack ice is visible in the lower strait with its southern limits extending southwestward from Disko Island, just off the west coast of Greenland, thence along

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the Coast of Labrador to where it blocks the entrace to the Straits of Belle Isle between the Island of Newfoundland and the mainland. Cumberland Sound, Frobisher Bay, and the northeastern side of the Hudson Strait, Ungava Bay, and all of Hudson Bay are completely ice covered with the exception of an elongated area of open water or very thin ice along the eastern side of Hudson Bay.

As is partly evident in figure 1, obscuration of Earth's surface by cloud is a significant problem in the interpretation of ice extent in satellite photographs. Skilled photo-interpretation, making maximum use of landmarks, cloud shadows and comparison of pictures of the same area on two or more successive days, or use of overlapping pictures from successive orbits, is necessary for proper and consistent discrimination between sea ice and clouds.

To automatically and objectively filter clouds from scenes containing ice or snow fields, a method known as minimum brightness compositing was developed. Composite Minimum Brightness (CMB) chart is derived by computer processing of the mapped satellite vidicon data for several successive days, usually five. Only the lowest brightness observed at each grid point during the compositing period is saved for final display. Since cloud-free land or ocean is much less reflective than ice, snow, or clouds, the compositing procedure tends to retain just the slowly changing ice and snow fields, effectively filtering all clouds except those relatively few that persist throughout the period.

The CMB chart is one of the end products of a series of complex data processing steps requiring a high-speed electronic computer. After digitization of the analog television signal from the satellite, the raw data are brightness-normalized for variations in the response of the camera system and for inequalities in solar illumination. The data are then mapped onto a polar stereographic map projection after elimination of overlapping portions of pictures from adjacent orbits. The original brightness (relative) scale of 64 steps is compressed to 15 steps during this process.

Figure 2 is the CMB chart for the 5-day period, May 9-13, 1970, Brightness values have been displayed with a gray scale of 15 steps from white to black. The brightest areas appearing on the CMB chart are ice and snow on Greenland, Iceland, Scandanavia, and elsewhere in areas north of the treeline. Solid pack ice, for example along the east coast of Greenland and in the Baffin Island and Labrador Coast areas, appears almost as bright. Some unfiltered cloudiness will be found on every CMB chart. Fortunately, it is usually distinguishable from snow or ice by being less bright and more ragged or irregular in appearance. Cloud areas also tend to show much more change from one period to the next than do snow or ice areas.

An alternative method of CMB display is by means of computer wherein the brightness values are printed at each point of the array (see fig. 3). When these values are calibrated with respect to external brightness "benchmarks," such as the Greenland ice cap and cloudfree ocean areas, in order to correct for variations within the system, they correlate highly with albedoes (reflectivities) obtained over sea ice by other means. As will be shown in the next section, differences in the CMB values are systematically related to differences in ice concentration and in ice condition (viz. snow-covered or puddled).

3. Quantitative Delimiting of Sea Ice Conditions

Computer printouts of CMB brightnesses were used to obtain data samples for various areas in the North American Arctic during the period mid-May through mid-September 1969. The southernmost group of areas studied included the following: central Hudson Bay, McClintock Channel, Foxe Basin, and northern Davis Strait. Much change occurred in ice conditions in these areas during the period. Another group consisted of areas near 75°N: northern Beaufort Sea, just west of Banks Isl., McClure Strait, western and eastern Viscount Melville Sound. These areas were characterized mostly by compact or very close pack throughout the period. Another group comprised areas varying in latitude from 68°N to 78°N, but all were characterized by very open pack or ice-free waters throughout the season: western Amundsen Gulf near Cape Bathurst, Chukchi Sea near Cape Lisburne, Barrow Strait just east of Resolute, and Smith Sound between Greenland and Ellesmere Island.

The data for a representative member of each of the above groups (see locations in fig. 4) have been represented in graphical form in figure 5; data for a Greenland ice cap area (Area G) are shown also. Note that the adjusted brightness averages for the ice cap are consistently near a value of 10 on a relative brightness or reflectivity scale of 0-14. The sample taken in western Viscount Melville Sound northeast of Banks Isl. (Area M) is just as bright as Greenland initially, and remains between 9 and 10 through the first third of June. Thereafter it drops rather rapidly in brightness to values between 6 and 7, maintaining this new level through early August. Throughout the remainder of the study period in mid-September it fluctuated between about 3 and 5. According to the Navy's BIRDS EYE Arctic Ocean Ice Reconnaissance Mission (4-69), which passed over this part of Melville Sound on June 3 and again on June 10, this area was characterized by the following ice conditions: 8/8 total concentration of fast ice, 5/8-6/8 multiyear, and 3/8-2/8 thick first-year; no openings, no melting. BIRDS EYE mission 5-69, which reconnoitered this area again on July 28, reported the following: 8/8 total concentration; 6/8 multiyear, 2/8 thick first-year; fractures, many puddles, and a few thaw holes. No BIRDS EYE data were available for August or September in the Melville Sound area, but weekly ice charts issued by the Dept. of Transport, Meteorological Branch of Canada for August show 10/10 concentration in this area, distributed by type as follows: 7/10-6/10 multiyear, and 4/10 or less first-year. Puddles, 3/10 frozen, were reported. During the first half of September the principal change in ice conditions was a decrease to 0/10 of first-year ice and the first appearance of new ice. There was also a trend toward freezing of puddles and the occurrence of snow cover.

In summary, western Melville Sound was characterized by high brightness values (equal to or approaching Greenland values) during the early part of the period when the ice pack was snow covered. Brightnesses decreased by about 30% when the snow melted and puddles developed in late June and through July. The brightness level diminished somewhat more in late August through mid-September as fractures and thaw holes appeared and some of the first-year ice melted. Some of the small peaks interrupting the general downward trend of brightness were associated with stormy periods when persistent cloudiness was not completely filtered by the compositing technique. The upturn in mid-September could also be related to the reported reappearance of some snow cover on the ice.

Central Hudson Bay in figure 5 (Area H) exhibits moderately high brightness averages, near 8, through mid-June, whereupon a remarkably steady decrease sets in, values reaching zero by the first of August. The brightness remains at or very near zero for the remainder of the study period. No BIRDS EYE data were taken over or near this area, so all comparisons are with the Canadian ice charts, the earliest available being for the week ending June 18. Concentrations were reported as 8/10 to ≥9/10, all first year ice, through mid-July, with 1/10-2/10 puddles and 1/10-2/10 thaw holes first being reported the last week of June. The total concentration decreased to 7/10, the fraction given as "medium floe or greater" steadily diminished from 5/10-10/10 to 2/10, and the percentage coverage of puddles increased to 5/10, through the month of July. In the first week of August there was an abrupt decrease in total concentration to 2/10 to 5/10, and by mid-August ice-free conditions were reported in central Hudson Bay.

In summary, the trend of adjusted brightness averages in central Hudson Bay is well correlated with the melting and decreasing concentrations of ice reported in that area.

The final study area given in figure 5 is southwest of Banks Island near Cape Bathurst (Area B) and is representative of those areas that tend to remain ice free throughout the period of study. The highest brightness averages here fell between 2 and 3, but much of the time the values were 1 or under. The high values in May were the result of shorefast ice along the east side of Cape Bathurst extending into the southwest corner of the sampling area. Movement of the sampling area less than 37 km to the NE would have brought the adjusted brightness averages in May to a magnitude of well under 1. The BIRDS EYE flight passed over this area on June 3, June 10, and June 29; in all cases the ice concentrations were reported as zero to ≤1/8. The weekly Canadian ice charts for June 18 through September 13 reported open water in this area southwest of Banks Island, with one exception. The chart for the week ending August 29 showed the sampling area within a narrow finger of 3/10 concentration.

In summary, ice-free conditions in this area were characterized by brightness averages generally ≤1/10 those typical of ice cap or snow covered compact or very close pack ice. Occasional peak CMB values of about 2, such as occurred once in July and several times in August, were associated with periods of persistent cloudiness.

Examination of adjusted CMB averages for a number of Arctic areas during the period mid-May through mid-September of 1969, in conjunction with ice reconnaissance data, ice charts, and meteorological data, indicates that characteristic brightness values are associated with different ice pack concentrations and conditions. These relationships are summarized in Figure 6. Residual cloudiness in the CMB charts presents a minor problem at the lower end of the brightness scale. Thus areas of very open pack or that are ice free may sometimes have brightness values of 2-4, which is the same level associated with open pack concentrations according to figure 6.

Scientists working in this field have stated that surface albedo and its variations are probably the most important regional factor affecting the heat and mass budgets of the Arctic Basin. Since it can be shown that adjusted CMB values derived from satellite vidicon data are highly correlated with albedoes obtained over sea ice by other means, the technique presented here promises to be a useful tool for sea ice researchers and forecasters.

4. Future Prospects for Remote Sensing of Sea Ice from Earth Satellites

Yet other techniques are being developed to extend and improve sea ice surveillance from Earth satellites. It has been shown that infrared radiometer data from NASA's Nimbus satellites can be used to detect major ice features in the darkness of the polar night when television cameras or visible spectrum radiometers are useless. Studies are continuing to determine optimum data processing and display methods to use with NOAA's ITOS scanning radiometer (SR) measurements. The ITOS SR can provide daytime or nighttime thermal infrared data (10.5-12.5 micrometers) at a maximum ground resolution of about 7.5 km and daytime visible data (0.52-0.73 micrometers) at a resolution of about 3.5 km.

The second-generation ITOS, planned to begin in 1972, is scheduled to carry a Very High Resolution Radiometer (VHRR) with both a visible spectrum (about 0.6-0.7 micrometers) and a thermal infrared (10.5-12.5 micrometers) channel. In contrast to the measurements from the SR on the current ITOS, the data from both the channels on the VHRR will have a maximum ground resolution of 925 meters. This significant improvement in resolution, which begins to approach that of the Earth Resources Technology Satellite (ERTS), should improve our capability for detecting and defining sea ice features, concentrations, and conditions.

The multispectral capability of the ERTS A system, also planned to begin in 1972, will be in the visual and near-infrared. It is uncertain at this time how much increase in information content will derive from the multispectral character of the ERTS observation in the case of sea ice applications. The further increase in ground resolution, to 100-200 meters, however, will yield yet better delineation of details in ice features. ERTS B, in 1974, is to be equipped additionally with a thermal infrared channel in the 10 micrometer water vapor "window" region.

Although the 50° inclination of its orbit will preclude viewing of polar areas, the manned NASA SKYLAB spacecraft, planned for late 1972 or early 1973, will carry an Earth Resources Experiment Package with a number of sensors of interest with respect to ice observations. There will be a 6-camera multispectral photographic facility and a 10-band multispectral scanner with more channels in the visible and near infrared, as well as one in the thermal infrared, and ground resolutions will come down in the vicinity of 50-100 meters. More nearly all-weather viewing of sea or lake and river ice should be possible by means of a 13.9 GHz microwave radiometer/scatterometer and a 1.4 GHz microwave radiometer. Even data from the infrared spectrometer could be useful in that it should be possible to determine which specific regions of the IR spectra have the greatest pack ice information content and discriminative capacity with respect to clouds.

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GLOSSARY

APT: Short name for Automatic Picture Transmission. Certain satellites of the TIROS and Nimbus series have had special camera and transmitter equipment such that television pictures and radiometer data taken while the satellite is within range of a station on Earth's surface can be received and displayed on relatively simple and inexpensive equipment.

Benchmark: A standard reference location or value used for calibration purposes.

Compact pack: Defined as 8/8 total ice concentration.

Compositing: Here it refers to the use of data taken over the same region but at different times.

Digitization: The process whereby a continuous analog signal received from the satellite is converted to discrete numerical values.

Fast ice: Sea ice that forms and remains fast, i.e. attached, to the shore. Fast ice can extend several hundred kilometers from the coast.

First-year ice: Also called "winter ice," this is ice that has formed during the current season, and it is generally less than two meters in thickness.

Medium floe: Ice floes 100-500 meters across.

Multi-year ice: Also called "polar ice," this is ice that has survived at least two summers, and it is generally two to four meters or more in thickness.

Multi-spectral: Refers to a sensor system that has two or more radiation detectors or camera films, each measuring in or sensitive to a different interval or band of the electromagnetic spectrum.

NOAA: National Oceanic and Atmospheric Administration (formerly ESSA), an agency of the U.S. Department of Commerce, which operates the National Environmental Satellite Service.

Puddled: Refers to a sea ice condition wherein melt water is evident on the surface of the ice.

Resolution: This term usually means "spatial resolution" or "ground resolution." It refers in simplest terms to the smallest detail detectible in satellite imagery of clouds or Earth's surface when there is reasonably good contrast between the target(s) and its background.

Shorefast ice: Same as "fast ice."

TIROS: Short name for Television and InfraRed Observation Satellite, a meteorological Earth satellite.

Water vapor "window": Those portions of the electromagnetic spectrum wherein water vapor in Earth's atmosphere is relatively transparent to, i.e. absorbs weakly, energy emitted from Earth's surface and atmosphere.

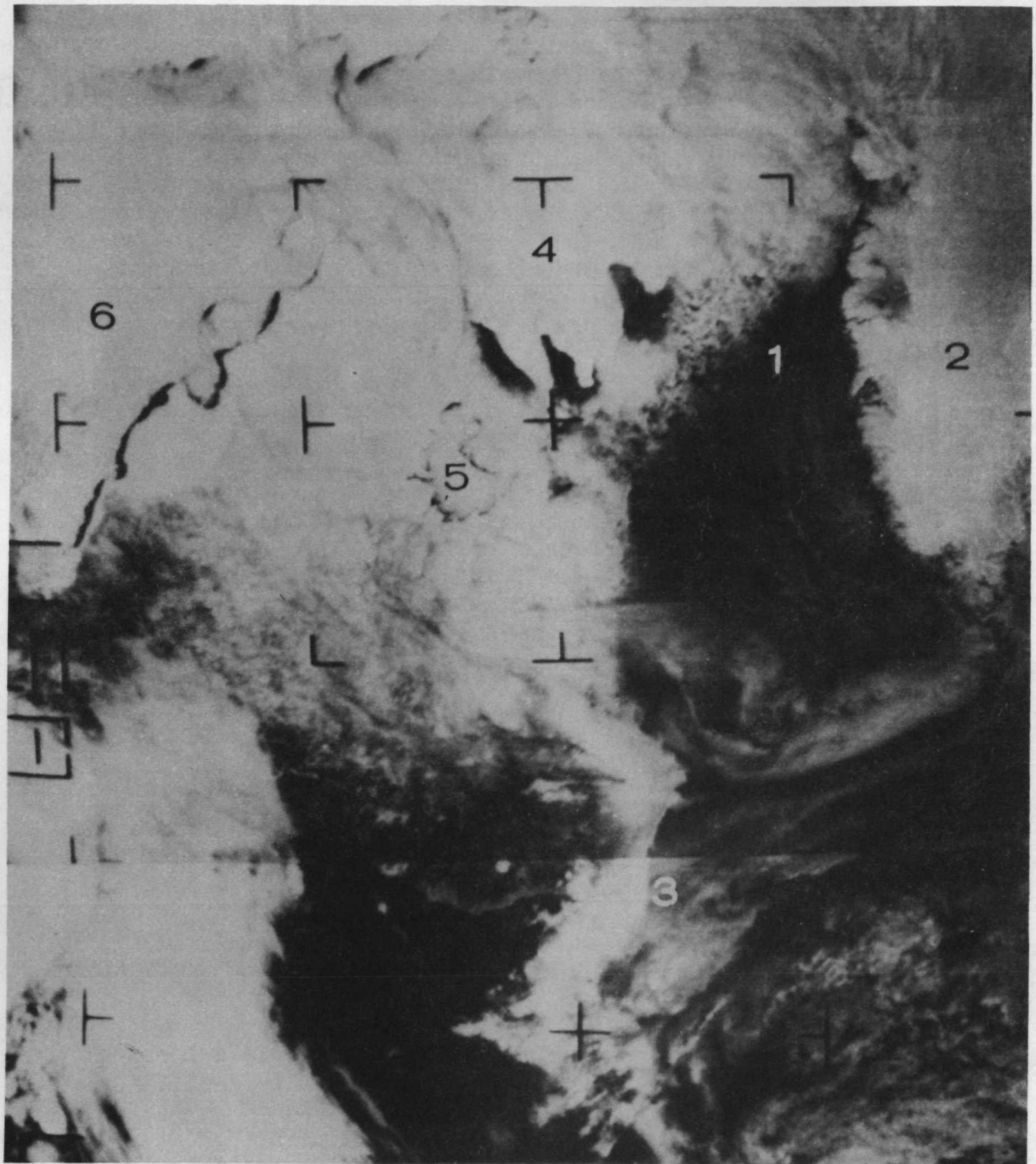
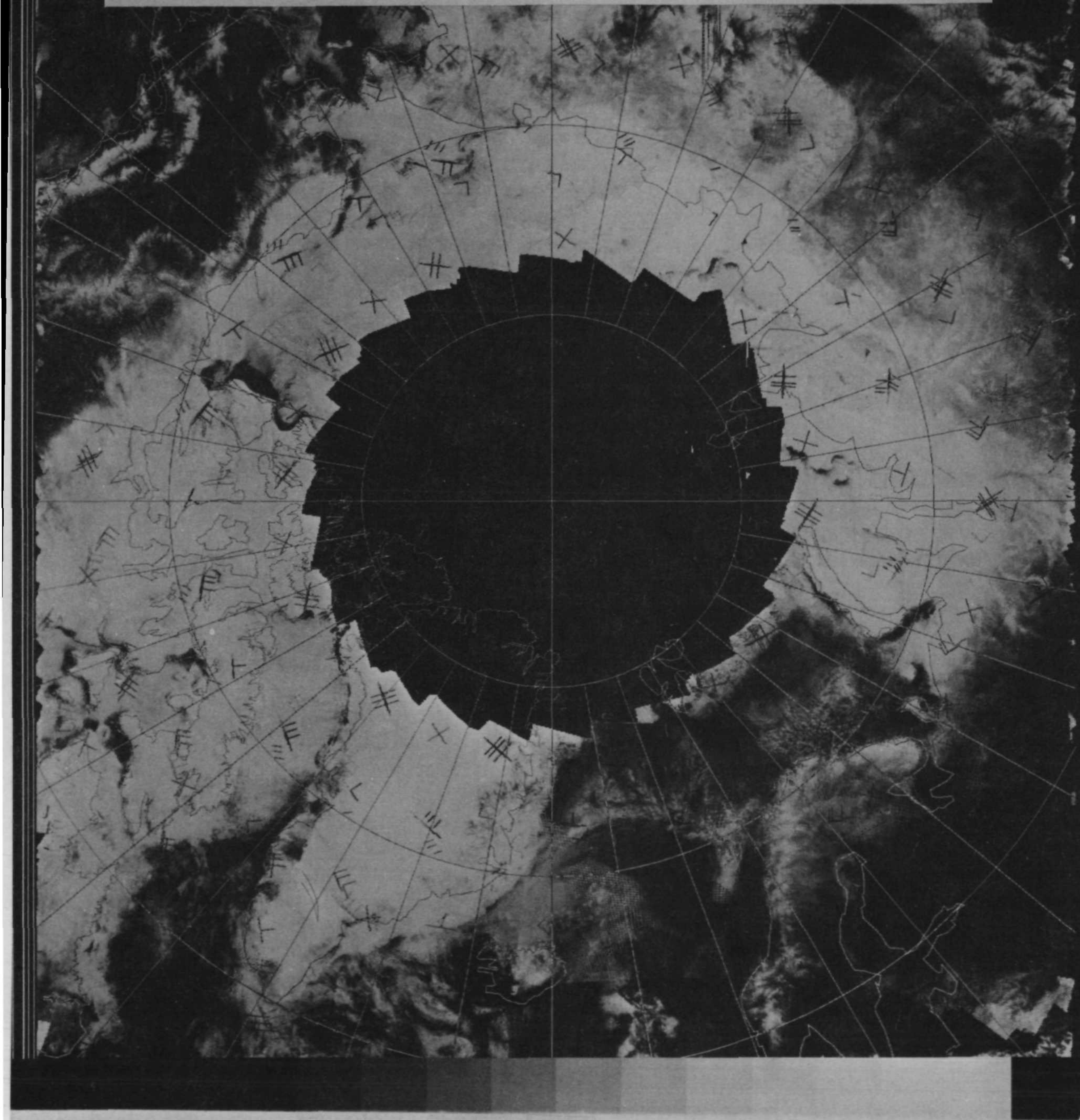


Figure 1.--Composite of two APT pictures from ITOS-1 taken on April 22, 1970. 1) Davis Strait; 2) Greenland; 3) Straits of Belle Isle; 4) Baffin Island; 5) Ungava Bay; 6) Hudson Bay.

Figure 2.--Five-day Composite Minimum Brightness chart for the period May 9-13, 1970, based on brightness data from the ESSA-9 satellite. The black area centered on the North Pole is a region where no data could be obtained because of insufficient solar illumination. Small "cross" or "T" marks are residual fiducial marks retained during the compositing process.



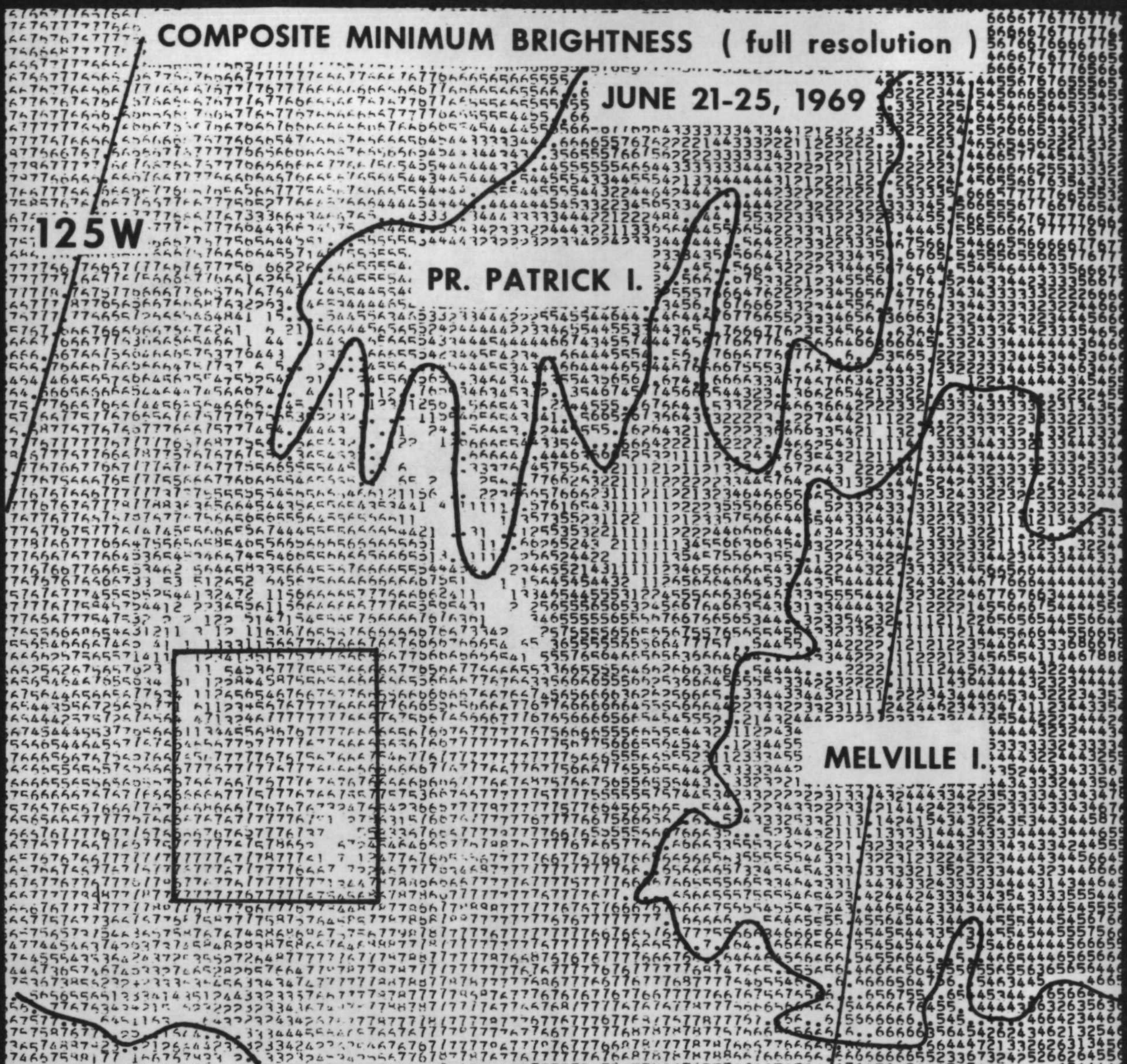


Figure 3.--Portion of a computer printout of the Composite Minimum Brightness (CMB) values for June 21, 1969. Rectangular block is approximately 40 n. mi. (67 km) on a side. The 15-step brightness scale is coded as follows: blank, 1, 2, 3, ... 9, A, B, C, D, E.

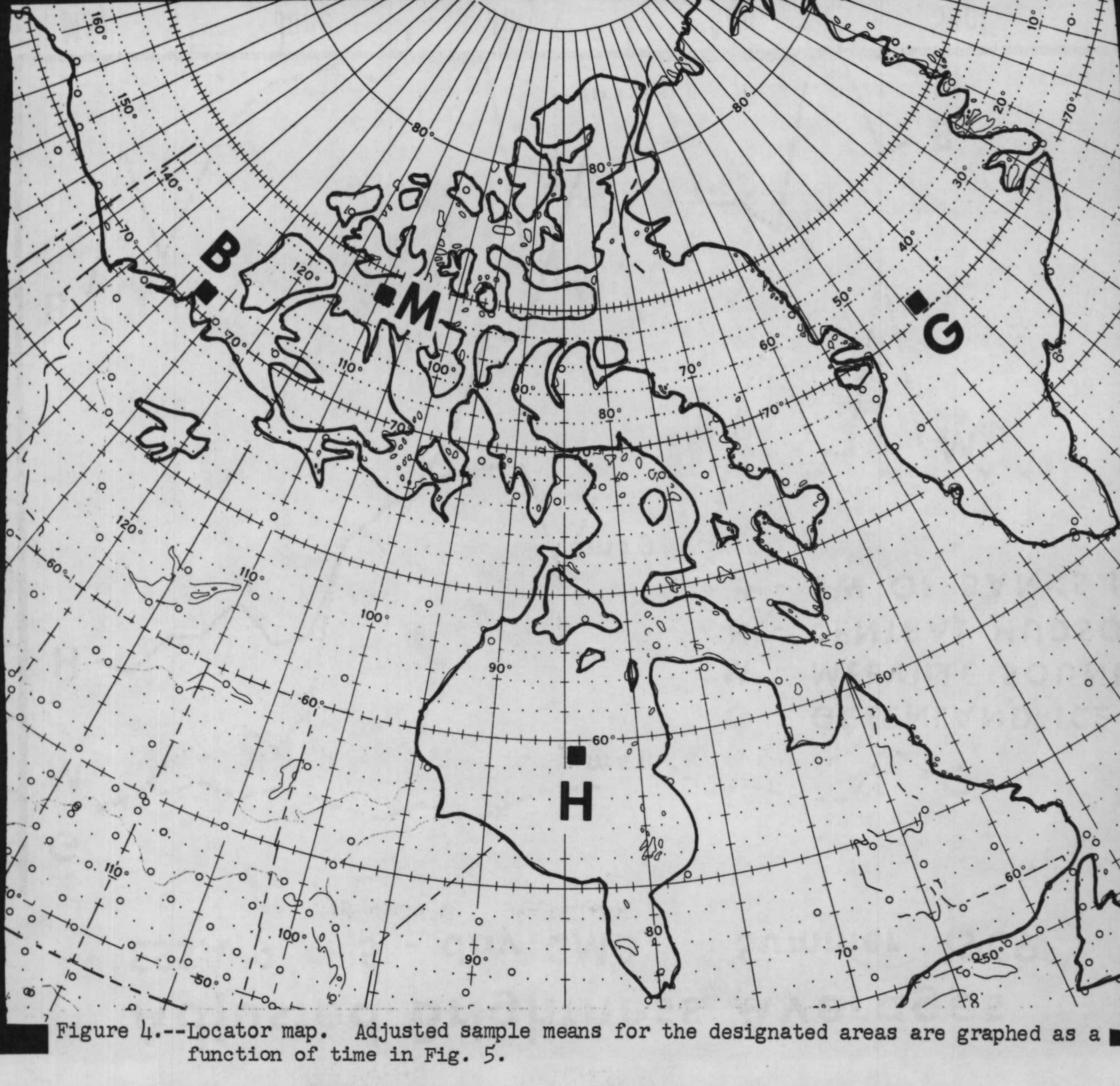


Figure 4.--Locator map. Adjusted sample means for the designated areas are graphed as a function of time in Fig. 5.

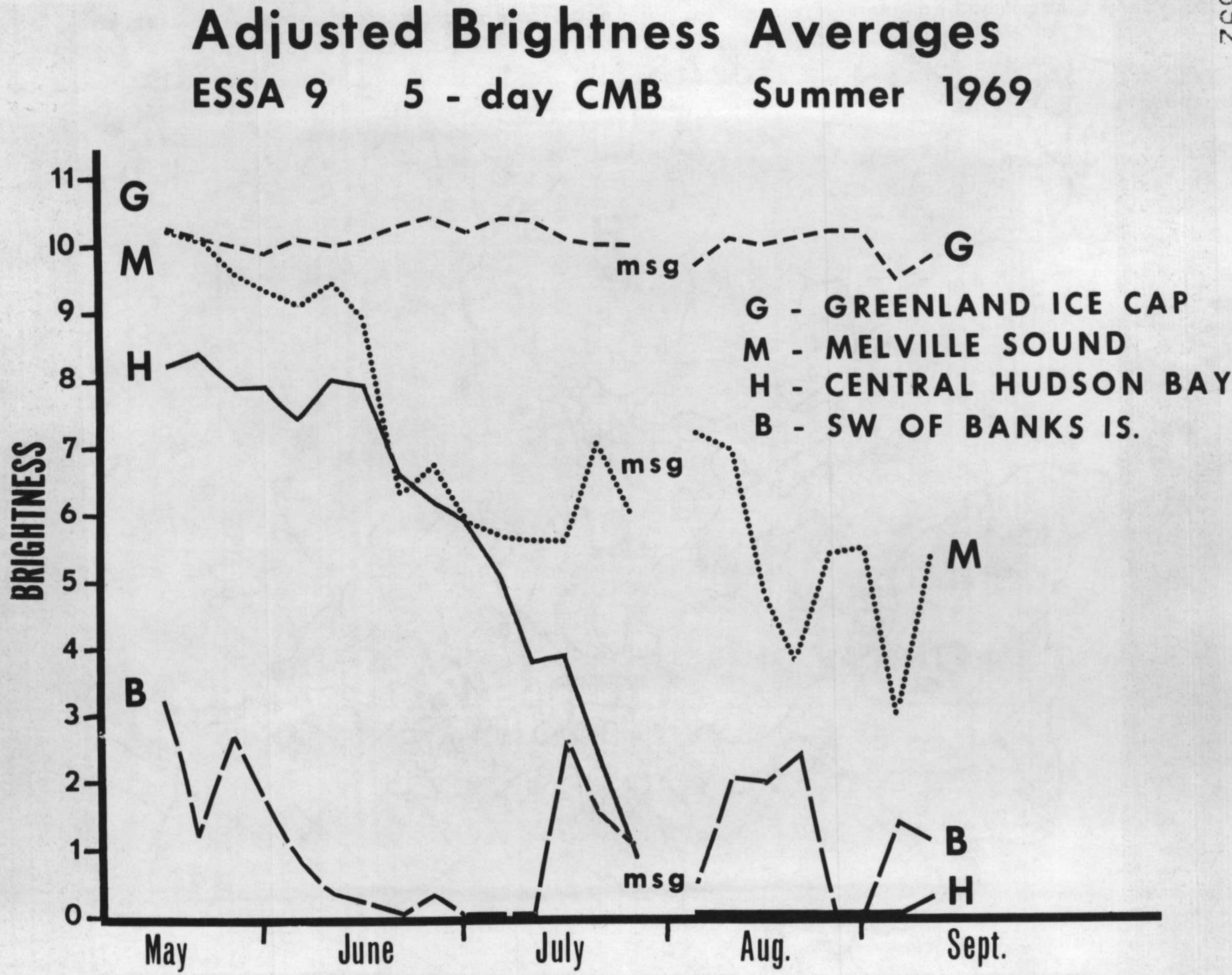


Figure 5.--Adjusted brightness averages for four Arctic areas (see locator map in Fig. 4) as a function of time for the period mid-May to mid-September 1969.

CATEGORY	ADJUSTED CMB AVERAGE	ICE CONCENTRATION	ICE CONDITION
1	9-10	COMPACT OR VERY CLOSE PACK (10/10-9/10)	SNOW COVERED (>7/10)
2	7-8	COMPACT OR VERY CLOSE PACK (10/10-9/10)	SNOW FREE (< 3/10); LITTLE OR NO PUDDLING (< 1/10)
3	5-6	VERY CLOSE OR CLOSE PACK (9/10-7/10)	SOME PUDDLES AND THAW HOLES (1/10-3/10)
4	2-4	OPEN PACK (6/10-4/10)	MUCH PUDDLING (>3/10) AND ROTTEN ICE
5	0-1	VERY OPEN PACK (3/10-1/10) OR ICE FREE WATERS	——

Figure 6.--Summary of relationship between adjusted CMB brightness averages and associated ice concentration and condition.