POLAR EXPLORATION WITH NIMBUS METEOROLOGICAL SATELLITE[1]

R. W. Popham[2] and R. E. Samuelson[3]

Authors' note: *The Nimbus I meteorological satellite was launched from the Pacific Missile Range in California on 28 August 1964. It was injected into an 81° retrograde, nearly sun-synchronous orbit with an apogee and perigee of, respectively, 933 and 423 km. Instrumentation included an Advanced Vidicon Camera System (AVCS), an Automatic Picture Transmission (APT) system, and a High Resolution Infra-Red (HRIR) system. On 22 September, owing to a spacecraft malfunction, the satellite ceased transmitting data. During its operational lifetime, nearly 15,000 AVCS and 1600 APT photographs were obtained, while HRIR photographs were acquired on 194 of the 368 usable data orbits.*

ONE OF THE problems encountered by the analyst interpreting weather satellite photographs is the interpretation of cloud patterns when viewed against a snow or ice background. One way to surmount this difficulty is to produce "background charts" which, in effect, show characteristic features of the surface as it appears under varying conditions of snow or ice cover. In attempting to do this, a number of interesting and significant studies have evolved; among these, the mapping of sea ice features has emerged as perhaps one of the most significant "by-products" of the meteorological satellite program.

In March 1961, a U.S. Navy Military Sea Transport ship was routed into Stephenville, Newfoundland. The routing was determined largely on the basis of TIROS II meteorological satellite photographs of sea ice. In February and April 1962, Canada and the U.S. conducted an extensive program (Project TIREC) to develop satellite ice reconnaissance techniques. During the spring of 1964, TIROS VII and VIII photographs were used to follow the break-up of ice in the Great Lakes. In August and September, 1964, some of the techniques developed during Project TIREC were used at a Canadian APT receiving station at Frobisher Bay, Baffin Island in an experiment to provide sea ice and weather information to ships operating between northern Hudson Bay and the Labrador Sea.

With Nimbus, the problem of cloud-snow-ice identification was extended to include the Arctic and Antarctic. Again, the same technique of identifying surface features was applied, this time to both the AVCS and HRIR

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[2]U.S. Weather Bureau, National Weather Satellite Center, Suitland, Maryland.

[3]Goddard Space Flight Center, Greenbelt, Maryland.

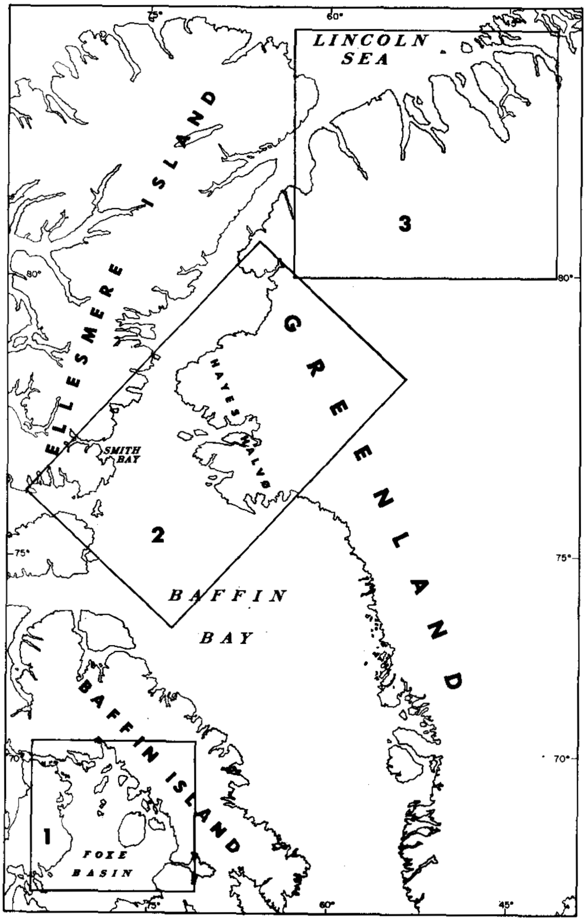


Fig. 1. Map of the Greenland-eastern Canada area. Areas blocked off are:
1. Foxe Basin region,
2. Smith Bay region and
3. Northwest Greenland region.

photographs. The relatively short lifetime of the spacecraft, and the difficulties encountered in producing gridded photographs, precluded construction of operationally useful weather or ice charts. The combination of high resolution AVCS photography, variable satellite altitude, low sun angle and nighttime IR photography resulted in the acquisition of a number of rather striking examples of meteorological, oceanographic, geological and geographic features in the polar regions.

The figures in this paper are representative of the Nimbus photographs acquired over areas previously unobservable from weather satellites. They illustrate the over-all nature and quality of observations and have been selected for their general scientific interest.

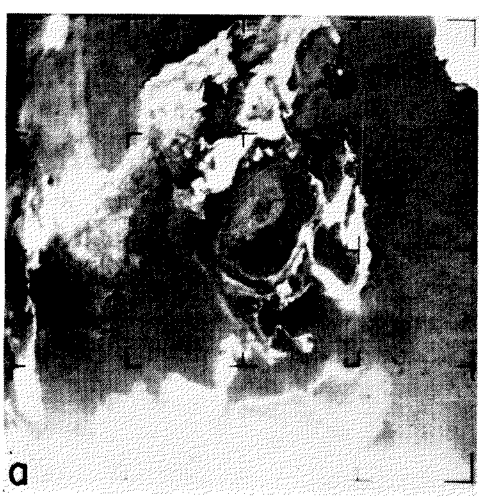
Most of the TIROS satellite ice reconnaissance studies have been carried out over Canadian east coast waters. Thus it is appropriate to begin our discussion of Nimbus ice photography in this same general area. Fig. 1 shows a map of this region; the three areas blocked off are areas for which we shall show examples of AVCS photography. Area 1 contains the Foxe Basin region, just north of Hudson Straits. This is the southernmost area of ice viewed by Nimbus 1 in the Northern Hemisphere. Area 2 is the general vicinity of Thule, Greenland; the area is one of the main arteries for ice movement from the Arctic Basin toward the North Atlantic. In area 3, the principal feature to be observed is continental ice, the Petermann Glacier in particular.

Fig. 2(b) shows the general Foxe Basin region. Note in particular Prince Charles Island just to the right of centre, and Air Force Island still further to the right. Fig. 2(a) is an AVCS picture of the same area, virtually cloud-free. The southwestern part of Prince Charles Island is located at the centre of the picture. The island itself is completely surrounded by an extensive ice field. The extreme brightness of this area is due in part to fresh, light snow covering the entire frozen region. Just to the north and northwest of Prince Charles Island we have the same effect. The extent of the ice as determined from this photograph is in very good agreement with sea-ice observations reported by the Canadian Department of Transport for 31 August and 2 September, 1964.

In the extreme upper right hand corner the southwestern edge of the Barnes Icecap on Baffin Island can be seen. The original photograph shows a very thin grey edge around the cap, believed to be the actual ice of the cap. The snow appears to have been melted off by the sun much as the snow on the southern and western slopes of mountains would melt first.

The U.S. Air Force Base at Thule, Greenland is located south of the two peninsulas shown in Fig. 3(b) (Area 2). Fig. 3(a) is an AVCS picture of the same area. The grey area on the left side is the leading edge of the ice pack which, by December 1964, completely engulfed the entire water area shown in this photograph.

For both long-range ice outlooks (3 months or more) and 30-day ice forecasts the ice forecaster makes use of degree-days, as well as any ice reports which can be obtained, to predict the movement, extent and thickness



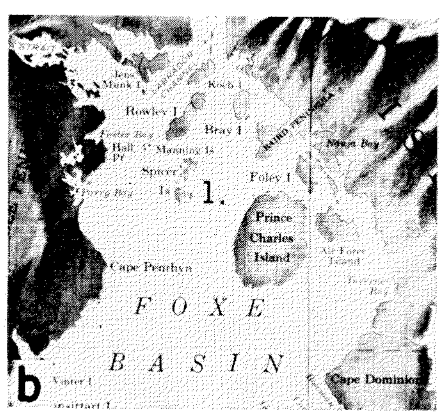


Fig. 2. (a) AVCS photograph, (b) map of the Foxe Basin region. 1425Z, 31 August 1964.

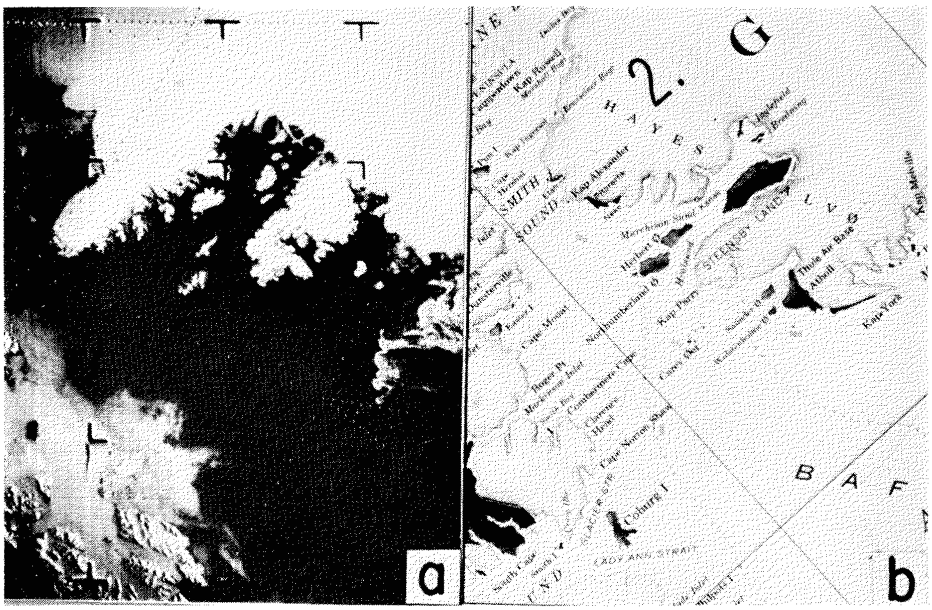


Fig. 3. (a) AVCS photograph, (b) map of the Smith Bay region. The grey area to the left in (a) is ice. 1445Z, 14 September 1964.

of the ice. The number of degree-days for a given locale is normally obtained from historical meteorological records. Sea-ice reports on the other hand, may be obtained two or three days apart, or a month or more apart, depending upon weather conditions, flying distance to the ice pack, etc. According to most experts in ice observing and forecasting, photographs of the type and quality shown here, if obtained regularly, could provide much of the sea-ice information at present acquired through aerial ice reconnaissance for preparing long-range forecasts. From these photographs the ice pack boundary can be plotted to an accuracy of within 3-7 miles, which is compatible with and in some instances better than the accuracy which can be achieved from aircraft over the open sea.

One of the more striking features of Nimbus photography is the pattern of sunlight and shadows resulting from a low sun elevation at polar latitudes. Examples of such shadows are illustrated in Fig. 4. Fig. 4(a) is an AVCS picture of the northwest Greenland area shown in Fig. 4(b) (area 3). Shadows produced by relatively high ridges and mountains are readily seen in the upper portion of the photograph.

The Petermann Glacier can be seen in the lower left corner of Fig. 4(a). Note the sharp and detailed outline of the shadows cast by the chain of mountains east of the glacier. We were able to estimate the heights of two of the peaks in this chain in the following manner:

The length of the shadows cast on the top of the glacier was measured with a micro-linear scale. After determining the scale of the photograph and

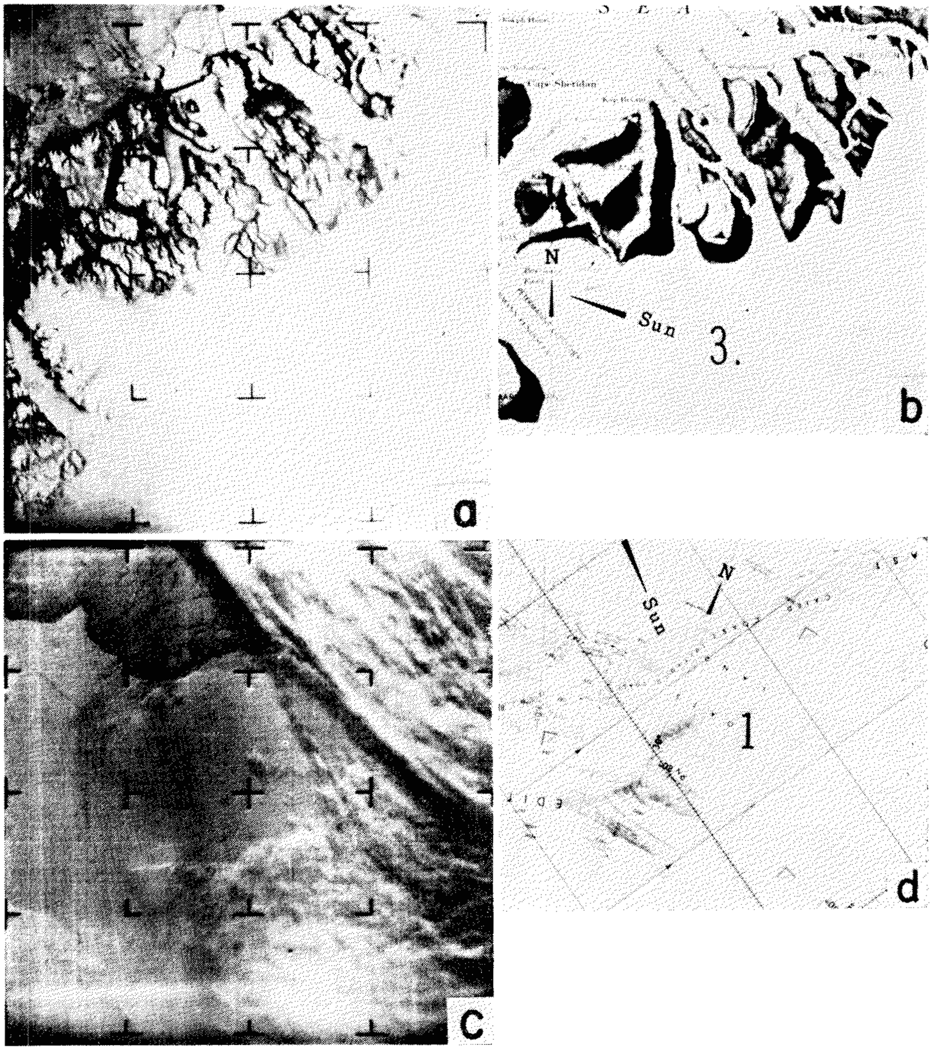


Fig. 4. (a) AVCS photograph and (b) map of northwestern Greenland. Petermann glacier is located in the lower left portion of the figures. 0945Z, 3 September 1964. (c) AVCS photograph, (d) map of the Coats Land region of the Antarctic. 1641Z, 13 September 1964. The direction of illumination by the sun is shown by the arrows.

the sun's azimuth and elevation angles, the heights of the peaks were determined geometrically. Computations showed one peak to be 3100 ft. high; the other, more southerly peak, 2600 ft. high. Since the shadows measured were cast on the top of the glacier, it is obvious that these heights are not the true heights of the peaks. If the two peaks are of the same height, however, we could deduce from these measurements that the top of the glacier was 900 ft. higher in the vicinity of the more southerly peak. It should be possible to determine the slopes of glaciers by this method if one knows the heights of surrounding mountains.

Unfortunately, at the time this experiment was performed, the true heights of these peaks were not known with sufficient accuracy to draw any definite conclusions. The only charts of this region available showed 3000-ft. contours in the vicinity of these peaks. From a close examination of Nimbus photographs of the Nile Delta region we know that the resolution of the centre camera of the AVCS is close to a quarter of a mile, and better in areas of high background contrast. For a resolution of one-quarter of a mile the estimated error in the measured heights of the two peaks is between 100-200 ft.

Another instance in which the method described in the preceding paragraphs might be applied is in the determination of cloud heights. A good illustration of a shadow produced by clouds is shown in Fig. 4(c). The figure corresponds to the Coats Land region of Antarctica, shown in Figs. 4(d) and 5 (Area 1). In the top centre of Fig. 4(c) a well-defined cloud shadow can be seen extending across the ice pack just off the coast. Cracks in the pack ice

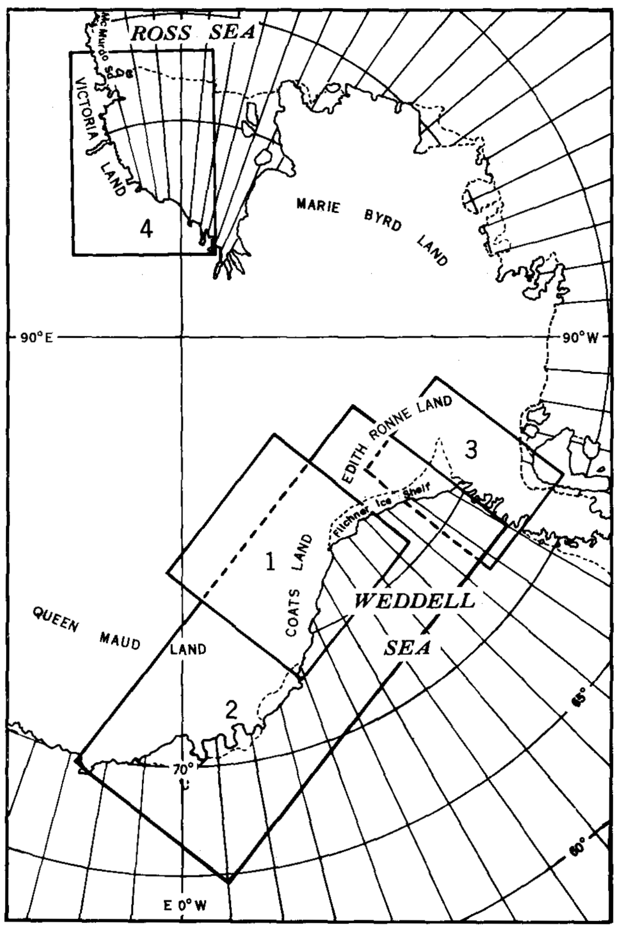


Fig. 5. Map of Antarctica showing:
1. Coats Land,
2. Weddell Sea coast,
3. Southeastern Antarctic Peninsula,
4. McMurdo Sound area.

are clearly visible. Using methods analogous to those of the preceding paragraphs the height of the top of the cloud casting the shadow was estimated to be approximately 6600 ft.

In contrast to the Arctic, relatively little is known about the Antarctic. Before discussing the Nimbus pictures obtained over the Antarctic a review of some of the known major facts about the continent seems appropriate.

Antarctica has the highest mean height of any continent: best estimates place it between 6000-6500 ft. high. Cold air flowing off the continent sometimes reaches hurricane speed at the coast. Average snowfall is only 5 inches (water equivalent) per year. Although a temperature of as low as $-88°C$. has been recorded in the interior, temperatures occasionally rise to a few degrees above freezing along the coast. This area is often referred to as the "Banana Belt" by people stationed in the interior of the continent.

If the Cascade Range were located in the Antarctic instead of North America, Mount Rainier (14,400 ft.) might appear as a hill 400 ft. high, and Mount Shasta (14,150 ft.) about 150 ft. high. Although not all of the antarctic glaciers are 14,000 ft. thick, many extend to sizable depths. Unlike the Arctic, where glaciers tend to calve off at the water's edge, antarctic glaciers may extend from a few miles to several hundred miles into the ocean, forming huge ice tongues or high ice shelves sometimes 600 to 800 ft. thick. The Ross Sea ice shelf is perhaps the best known example, but much of the apparent coastline of Antarctica is in fact a series of ice shelves.

The continent of Antarctica is outlined in Fig. 5. Area 1 in the figure has been shown in Fig. 4(c) and (d). Areas 2 to 4 are shown respectively in Figs. 6 to 8.

Fig. 6 (area 2) is an AVCS photograph of the apparent coastline of the Weddell Sea, which is actually comprised of the Filchner ice shelf and the seaward extension of smaller glaciers along the coast. This, in effect, forms a semi-permanent coastline, and is generally shown as a fixed feature on charts of the Antarctic Ocean. Some portions of the coast have not been mapped for several years, one observation dating as far back as 1939.

The great number of cracks in the pack ice is evident on all AVCS photographs of pack ice in the Antarctic. The pattern shown by these cracks

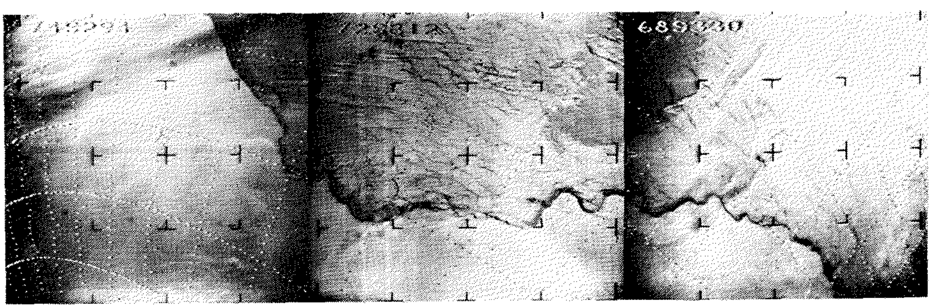


Fig. 6. AVCS photographs of the Weddell Sea. Cracks in the pack ice are readily apparent. 1630Z, 10 September 1964.

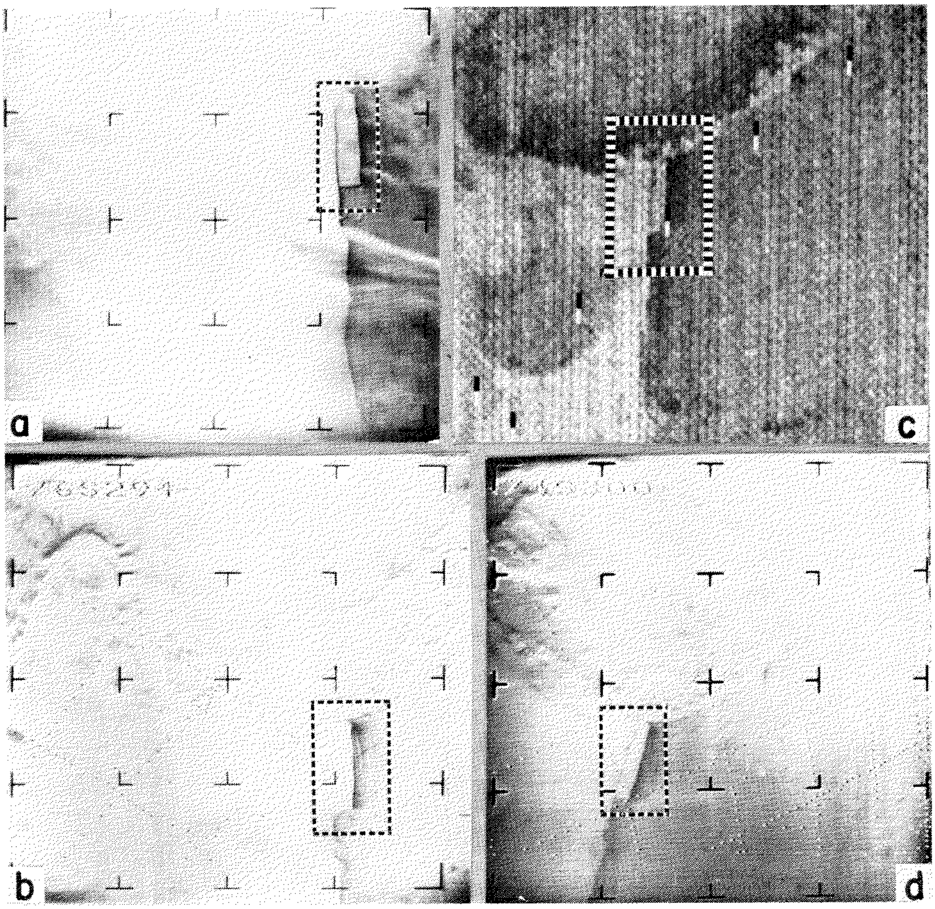


Fig. 7. AVCS and HRIR photographs of an iceberg in the Weddell Sea area; first known satellite photographs ever obtained of an iceberg. (a) AVCS, 1834Z, 8 September 1964, (b) AVCS, 1831Z, 16 September 1964, (c) HRIR, 16 September 1964, (d) AVCS, 2008Z, 16 September 1964. The contrast in (c) is typical of HRIR photography over the Antarctic.

is a good indication of the stresses and strains set up in the ice itself. Temperatures inferred from the Nimbus HRIR data are generally in the range 242-245°K. for the pack ice, in contrast to the 228-238°K. range of surface temperatures for the Antarctic continent proper. These differences in the effective radiometric temperatures appear to be entirely real, and not caused by any difference in the emissivities of surface materials.

The apparent coastline as shown in Fig. 6 is generally evident around the entire periphery of the continent. That the ice is very thin along this border, or that we are actually seeing open water, is given support by the temperatures inferred from the HRIR data. These temperatures range from 259-272°K., the lower temperatures prevailing in all cases where the apparent coastline is not wide enough completely to fill the field of view of the radiometer; in these cases contributions from regions lying outside the immediate

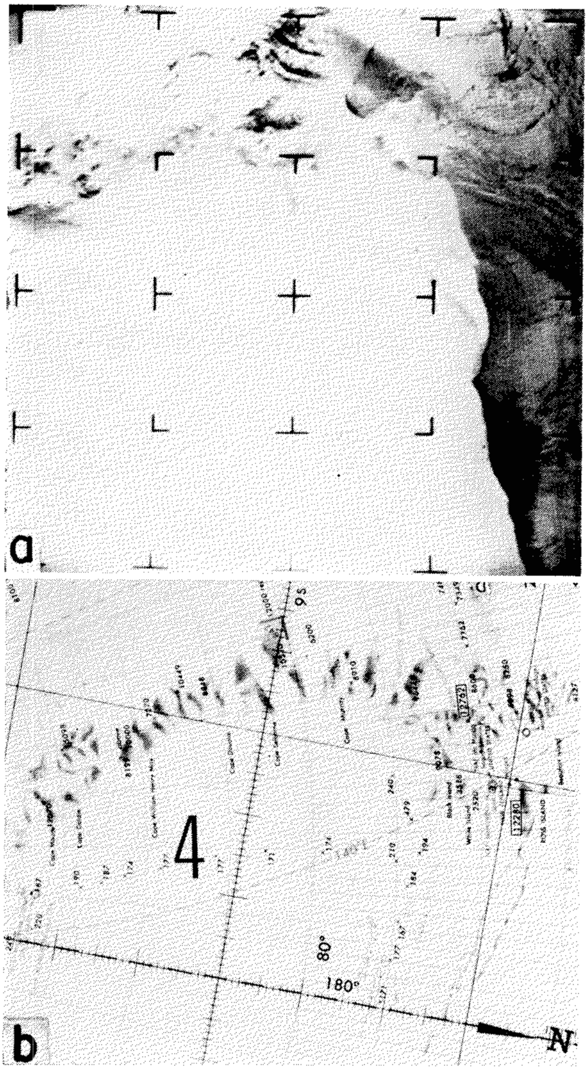


Fig. 8. (a) AVCS photograph, (b) map of the McMurdo Sound region (area 4) showing Ross Island (upper right of photograph), the Taylor and Wright dry valleys (dark parallel features near upper centre), and edge of the Ross Sea ice pack (along right side of photograph): 0355Z, 19 September 1964.

border add to the detected radiation, thereby reducing the inferred effective temperature. In those cases where the border is wide enough completely to fill the field of the HRIR radiometer, temperatures in the range 270-272°K. are consistently inferred from the radiation data. The ice cracks, although distinctly warmer than the surrounding pack ice, are not wide enough to allow reliable temperature determinations.

The first known case in which an iceberg has actually been photographed from a satellite over either the Arctic or Antarctic is shown in Fig. 7. It appears to have calved off the Filchner ice shelf near the southeastern end of the Palmer Peninsula (or the Antarctic Peninsula, as it is now known). It is approximately 70 miles long and 15 to 20 miles wide. From its dimensions we can estimate that it is probably about 200 ft. high.

The pictures in Fig. 7(b) and 7(d) were taken about 1½ hours apart, and 8 days later than the picture in Fig. 7(a). The dark region on the seaward side of the berg is not a shadow. We know this even without checking the sun angle, because the HRIR photograph in Fig. 7(c) shows the same effect, indicating that the dark region is either comparatively warmer than its surroundings, or that the emissivity of the region is much higher than that of the surrounding area. The crack between the berg and the ice shelf proper also appears warmer than the surrounding region.

Fig. 8(a) shows two very interesting geological features on South Victoria Land near McMurdo Sound. These are the rather famous Taylor and Wright dry valleys (dark, short parallel features near top centre of photograph). These valleys are glacier-carved and almost completely free of ice and snow; they do contain some small frozen fresh-water lakes. The dividing ranges are also almost completely ice-free, while the surrounding areas are fully glacierized. The edge of the glaciers for which the valleys are named are found at the head or western end of the valleys.

In general both the AVCS and HRIR photographs from Nimbus are of excellent quality, and coverage over the Antarctic is fairly complete. The Antarctic ice pack as delineated by Nimbus photographs is being mapped at the Polar Meteorology Branch, AAL, OMR. Fortunately the functional lifetime of Nimbus I corresponded closely to the time of maximum extent of the ice pack, and it is interesting to note that the area of the pack shown by the AVCS pictures agrees quite well with earlier charts of the maximum extent of pack ice, which must have been based on quite limited data. The HRIR photographs are now being examined to attempt a more accurate delineation of the ice pack, and in particular to attempt resolution of some doubtful areas where interpretation of the AVCS photos is open to question. Such maps, together with an analysis of cloud cover over the south polar region, could be most helpful in studies of the meteorology and oceanography of the entire Antarctic. Surface temperatures and snow and ice emissivities as determined from HRIR data should yield a wealth of information about actual surface characteristics. We have in the Nimbus spacecraft a remarkable tool in evaluating many of the interesting and important features of one of the last frontiers on the Earth's surface.

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