

ICE OBSERVATIONS BY THE *TIROS II* SATELLITE AND BY AIRCRAFT

D. Q. Wark*, R. W. Popham*, W. A. Dotson†, and K. S. Colaw†

Introduction

EARLY photographs obtained from the meteorological satellite TIROS I in April 1960 revealed areas in the Gulf of St. Lawrence and the St. Lawrence River that appeared to be partly covered by ice. Comparison of the TIROS I photographs with aerial ice reconnaissance charts for these areas, obtained from the Canadian Meteorological Service, confirmed the initial assessment (Wark and Popham 1960). Because the satellite was spin-stabilized and the optic axes of the cameras were parallel to the spin axis, orbital and spin precessions moved the viewed areas rapidly into the southern hemisphere. Additional photographs of the Gulf of St. Lawrence were not obtained until late in May 1960, when the ice was gone. No further study of the potential of satellites for ice reconnaissance was possible with TIROS I.

TIROS II was launched on November 23, 1960 into an orbit almost identical with that of TIROS I. Its nearly circular path is inclined 48° to the equator and its mean altitude is 690 km. The narrow-angle camera, employed exclusively in this study, subtends 12.7° in the diagonal.

The U.S. Weather Bureau and the U.S. Navy Hydrographic Office, in co-operation with the Commander Barrier Forces Atlantic and with the National Aeronautics and Space Administration, planned concurrent observations of the Gulf of St. Lawrence region from TIROS II and from aircraft. Aircraft observations provided visual records of ice and cloud conditions and in addition some aerial and radar photographs. Simultaneously TIROS II photographs were taken; a picture-taking interval of 10 seconds gave an overlap of the frames, so that strip mosaics could be constructed. The first series of observations was made late in January 1961; during the next favourable period, late in March 1961, another excellent series was made.

Observations

Satellite photographs were taken on January 24, 25, and 26 during passes 911, 926, and 941, respectively; in the period March 21 to 29 photographs were again taken during 11 passes. Fig. 1 shows the paths of the picture centres of the TIROS II photographs for those passes that have been selected for discussion in this account; the viewed areas extend 30 to 40

* U.S. Weather Bureau, Washington, D.C., U.S.A.

† U.S. Navy Hydrographic Office, Washington, D.C., U.S.A.

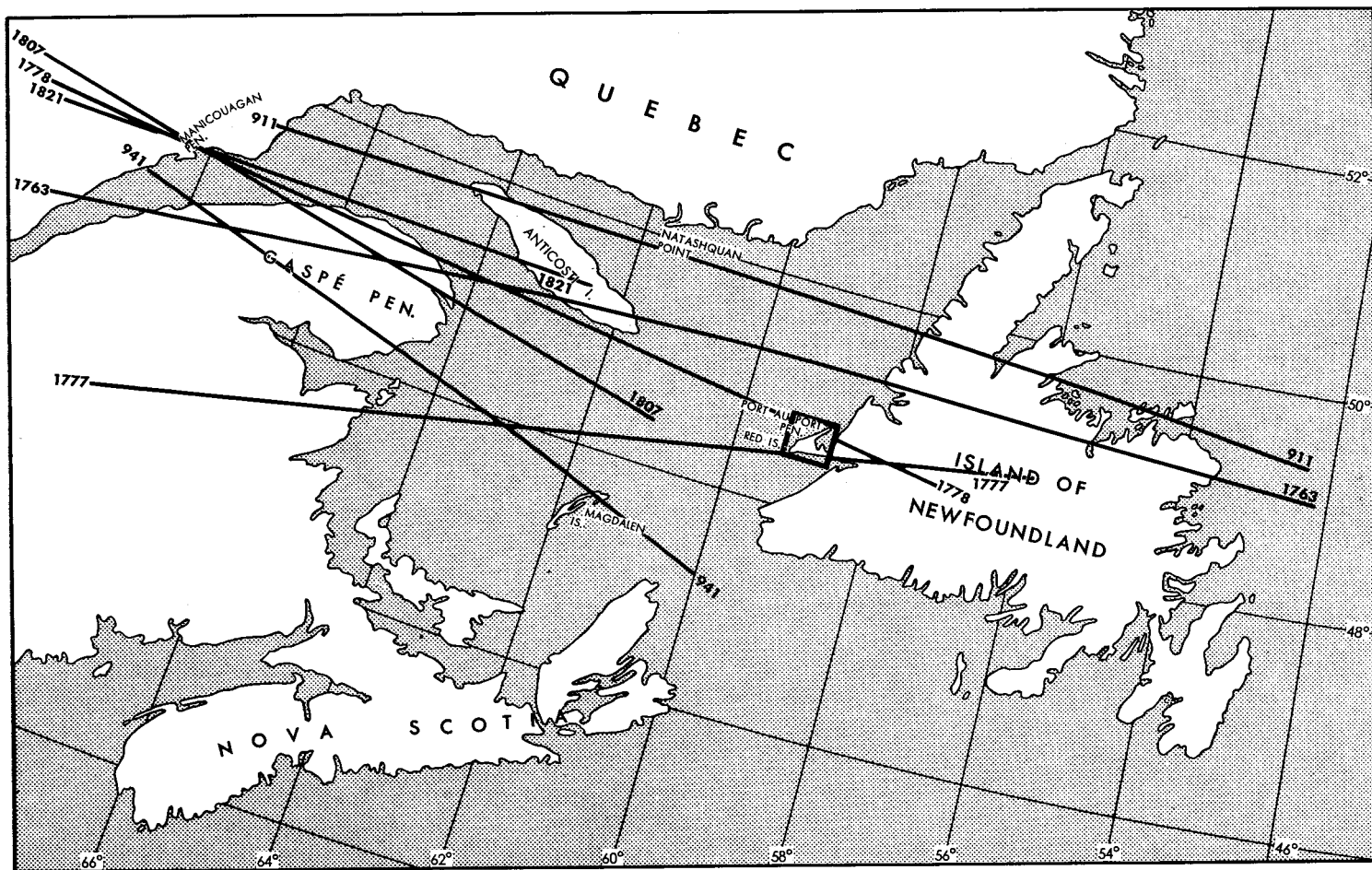


Fig. 1. The area of TIROS II ice studies. The lines connecting the centres of the pictures of the seven sequences selected for this discussion are shown and identified by the pass (orbit) number since launching. The strip viewed is about 60 to 80 miles wide. A small box on the southwestern coast of Newfoundland indicates the area photographed by a reconnaissance aircraft on March 24, 1961 (Fig. 9).

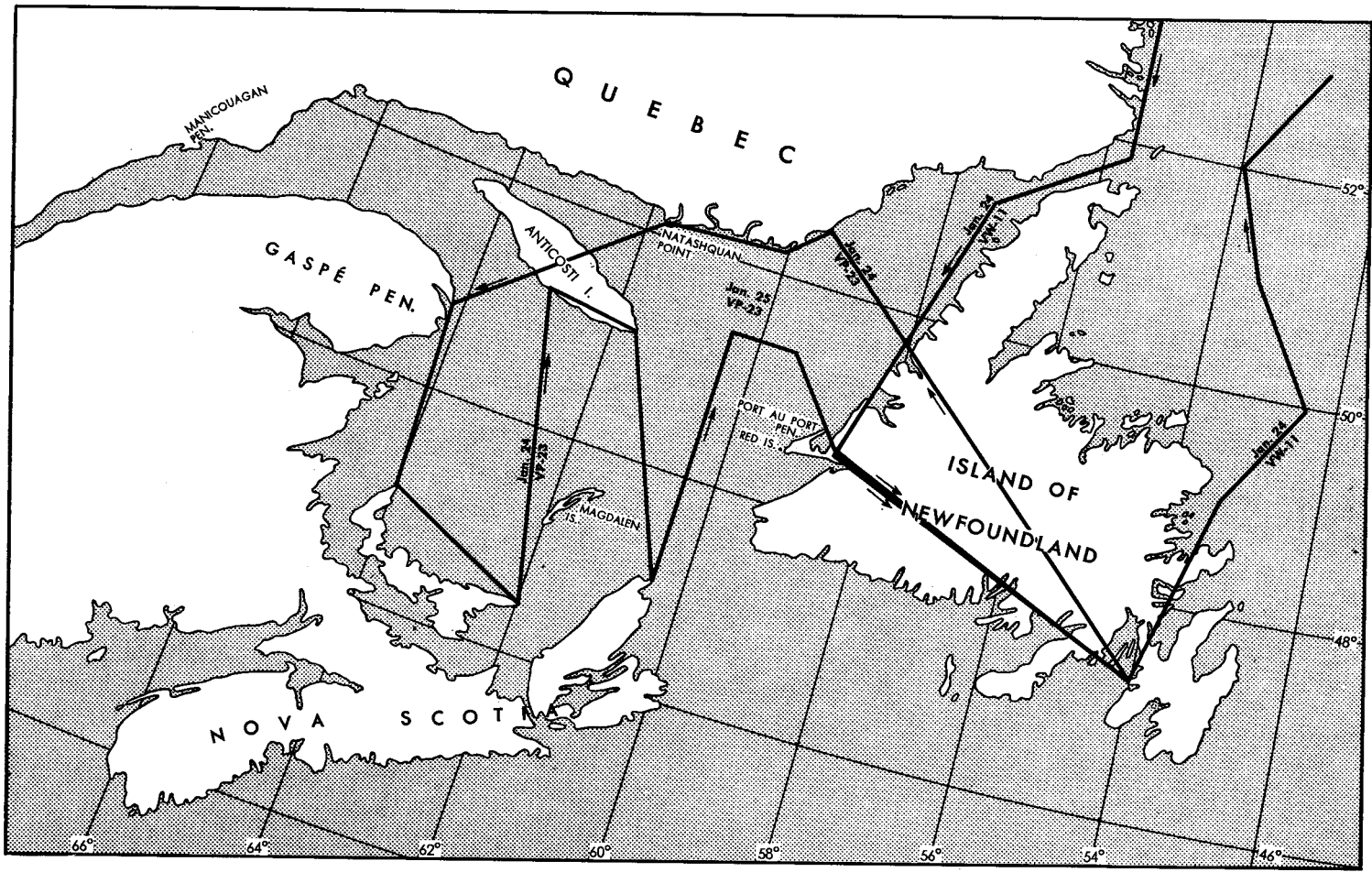


Fig. 2. U.S. Navy aircraft reconnaissance on January 24, 1961. Two aircraft, based at Argentia, Nfld., flew tracks over the Atlantic and over the Gulf of St. Lawrence to obtain ice and cloud information in the area to be viewed by satellite on pass 911.

miles on each side of the paths of the picture centres, which are shown as solid lines in the figure. The box off the southwest coast of Newfoundland is an area photographed in an aerial mapping survey on March 24 at the same time as the passage of the satellite; approximately 100 photographs were taken in this area for the purpose of mosaic construction.

Fig. 2 shows the flight tracks taken by two U.S. Navy aircraft in making visual observations of ice and clouds on January 24, 1961, the same day as pass 911. The tracks were laid out for maximum coverage in the region of the satellite photographs.

Weather is a controlling factor in ice observations from satellites. During the period January 24 to 26 the weather over Newfoundland and the Gulf of St. Lawrence was affected by two major pressure systems, a large High over the north-central U.S. and a Low over the ocean south of Davis Strait. The High drifted eastward and weakened, while the Low remained stationary and intensified. As a result the entire area was only partly cloudy on January 24, becoming mostly broken to overcast on January 25 and 26; the western area of the gulf, however, in the vicinity of the Gaspé Peninsula, remained clear or only partly cloudy. Surface winds were primarily westerly and northwesterly during this period and increased in intensity as the Low deepened.

During the March sequence the western part of the gulf was predominantly cloud-free. The eastern part was more directly influenced by a series of low-pressure systems that moved northeast along the U.S. coast, intensified and moved eastward into the Atlantic, passing just south of Newfoundland. The 1500 GCT surface chart for March 21 showed one of these Lows centred about 200 miles south of Newfoundland and a 1032-mb High over New England, with a ridge of high pressure extending northeast across New Brunswick and Quebec. The best series of satellite photographs during this period was obtained on March 23 when this high-pressure system was centred over the western Gulf of St. Lawrence. During the next two days, as this High degenerated, a second, more intense Low developed near Cape Hatteras, moved up the coast and remained quasi-stationary about 250 miles southeast of Newfoundland. A weak high-pressure ridge lay over the western gulf area on March 28. These were the dominant weather systems that influenced satellite observations during this period. Fig. 3 shows the symbols and abbreviations used in the illustrations for the following discussion.

Results and analysis

The central part of Fig. 4 shows a strip mosaic of satellite pictures taken on pass 911 on January 24; the pictures have been numbered for easy reference. Anticosti Island is visible in the first 3 pictures; the southern coast of Quebec is seen in the first 6; the western Newfoundland coast is seen in picture 7; pictures 8 to 13 show the eastern Newfoundland coast,

Notre Dame Bay, and part of the Atlantic. The ice reconnaissance data for the same day, as they are normally reported and plotted, are shown in the upper part of Fig. 4; the lower part of the figure shows the cloud coverage as observed from the reconnaissance aircraft. It should be noted that both the ice and cloud data were gathered during a flight of several hours' duration, whereas the satellite pictures were, for practical purposes, taken instantaneously. Therefore, exact agreement between the cloud formations as depicted by the reconnaissance and as revealed by the satellite should not be expected. On the other hand, the ice observations should agree closely with the satellite photographs because of the relatively slow processes involved in forming and moving of the ice.

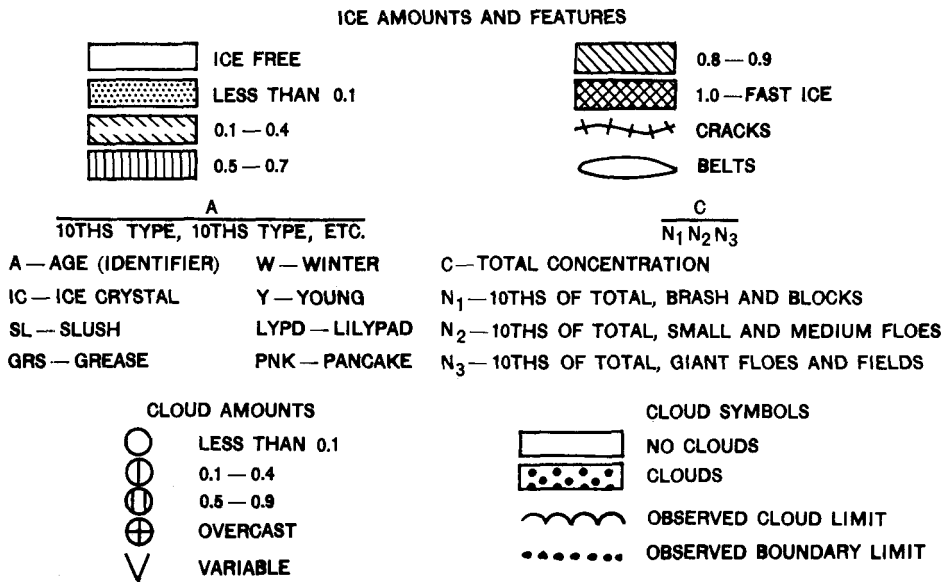
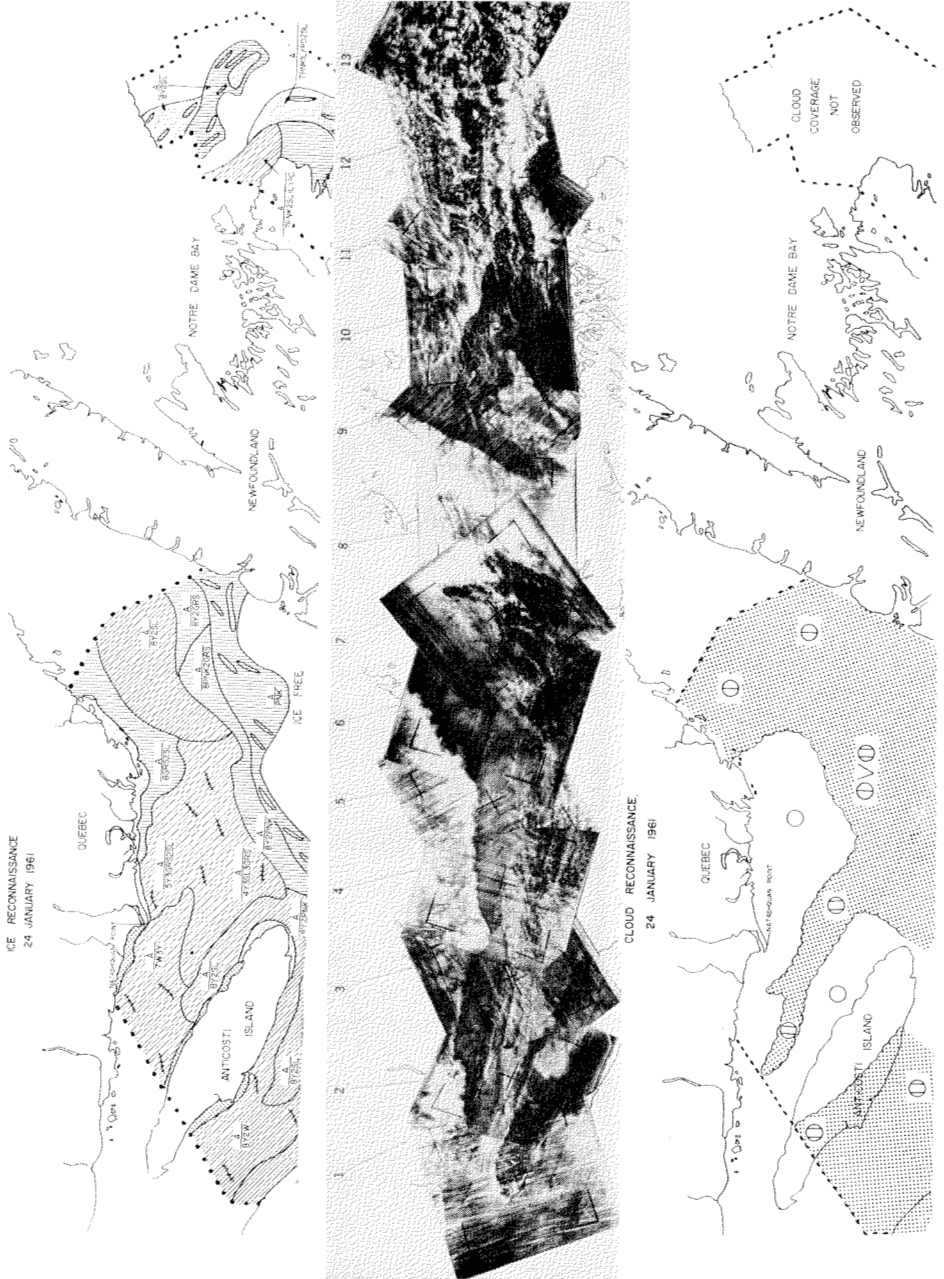


Fig. 3. Key to the symbols and abbreviations used in Figs. 4, 6, and 7.

Satellite picture 1 of Fig. 4 reveals fast ice (standard ice terminology is used, following U.S.N.H.O. Publ. 609, 1952), that is attached to the shore or grounded in shoal water, outlining the coast of western Anticosti Island, and a few parallel cloud bands oriented roughly WNW-ESE both north and south of the island.

In pictures 2 and 3 clouds in east-west bands, covering the area from the island to about mid-way to the Quebec coast, obscure the ice below them; only by means of the aircraft ice reconnaissance data is it possible to say with confidence that ice existed below these clouds. From the mid-way point, however, the skies are clear and ice is easily identified—it appears darker than the cloud-covered ice and displays a dendritic pattern caused by large cracks and leads in the ice. The ice reconnaissance shows an 0.8 to 0.9 concentration of ice in this area, 70 per cent of which is winter

Fig. 4. Simultaneous observations on TIROS II and aircraft January 24, 1961. In the centre is a strip mosaic of the satellite photographs from pass 911, extending across the Gulf of St. Lawrence and Newfoundland into the Atlantic. The visual ice and cloud observations for the same area are shown at top and bottom, respectively.



ice (more than 8 inches thick and white in appearance), and 30 per cent young ice (2 to 8 inches thick and grey to black in appearance), a transitional stage in the development of winter ice. The narrow, dark line adjacent to the shore-line suggests the presence of a shore lead, an open-water area between the land and floating ice. This cannot be verified, however, because it ends near the limit of the observations. The large bright spot on Anticosti Island is a snow-covered area of sparse vegetation that has been observed repeatedly by the satellite.

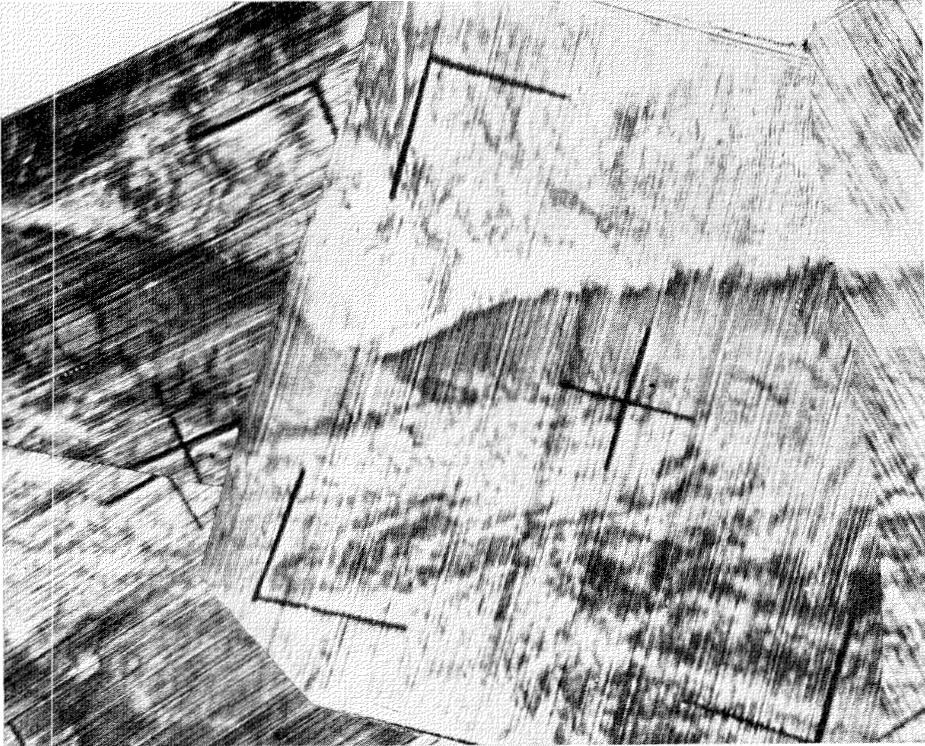


Fig. 5. TIROS II photographs of the Natashquan Point area, from pass 911. A shore lead and other cracks and leads are seen. Clouds lie along the bottom.

The area around Natashquan Point, seen on picture 4, Fig. 4, has been reproduced at a larger scale in Fig. 5. The aircraft from which the cloud and ice observations were made was approaching Natashquan Point from the east at an altitude of 10,000 feet when the satellite pictures were taken (1453 GCT). Natashquan Point is easily identified just left of the centre of Fig. 5. No clouds were present over the land, but the snow covering the numerous small lakes and unforested land in this region appears in the satellite pictures to be at least as bright as the cloud-covered ice in the Gulf

of St. Lawrence. The edge of the clouds stands out clearly about 5 miles south of Natashquan Point (the lines forming the fiducial marks on the pictures correspond to about 10 to 15 miles). These clouds, as well as all the others in the gulf, according to the aircraft observations, were cumuli-form, with bases at 3000 feet and tops at 5000 feet; they dominate the lower half of Fig. 5, and in many places show a banded configuration. The dark line along the coast is a shore lead, as verified from the aircraft; this dark line has the same appearance as that seen in pictures 2 and 3 of Fig. 4, permitting the confident interpretation of the latter as a shore lead also. The ice seen between the coast and the clouded area is relatively dark, a characteristic of the young ice that exists in large quantities there. Cracks and leads are evident, particularly on the far left, where there is a greater proportion of winter ice.

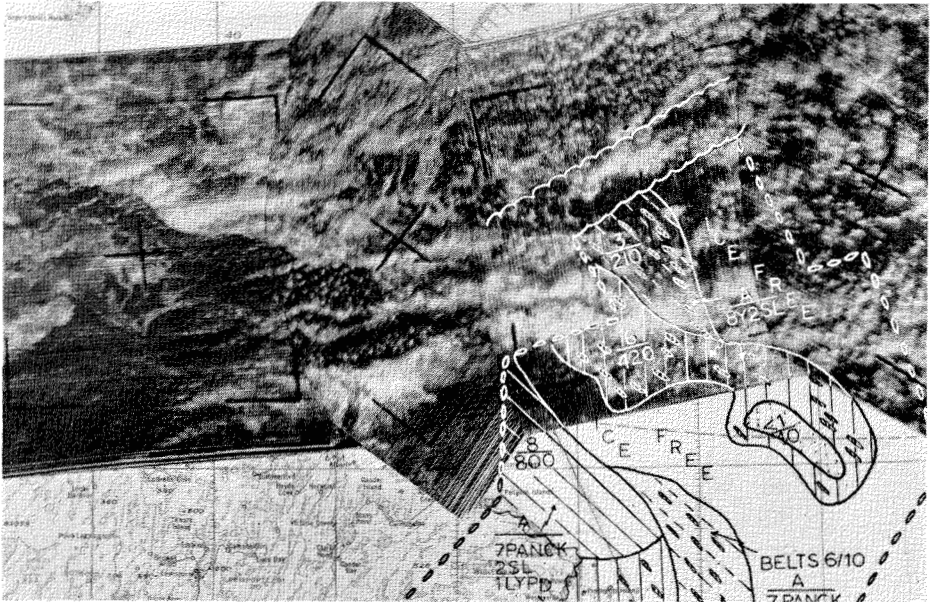


Fig. 6. TIROS II photographs of the Atlantic area off Newfoundland, from pass 911. The edge of the pack-ice is clearly seen (left of centre), as well as other features such as the belts and patches east of the tip of land (left, south of the pack-ice). On the right is superposed the aerial reconnaissance showing ice and clouds.

Most of the area seen in pictures 6 and 7 of Fig. 4 is cloud-free. The now familiar pattern of large cracks and leads can be discerned in picture 6, whereas picture 7 shows, in the lower half, a large area of more open water, about 50 per cent of which is covered with belts and patches of sea-ice; random clouds appear along the Newfoundland coast in the lower part of the picture, and east-west bands in the upper part.

The eastern part of Fig. 4 has been reproduced in Fig. 6, with the ice reconnaissance superposed. The most significant single feature of this mosaic is the sharply defined boundary of the sea-ice pack, running roughly east-west, clearly visible near the centre of the first 2 pictures but partly obscured by clouds on the last 2. Although the boundary of the ice pack usually marks the edge of extensive fields of solid ice, here the area within the pack contains large open-water areas, the ice pack having been broken up partly by the effects of the 50- to 60-knot winds that had been blowing over this area for the previous 3 days. South of the pack boundary, immediately below the centre cross on the first picture, is a fine example of belts and patches — meandering white or grey ribbons of ice seen against the darker background of the water, shaped by the wind and currents. In the reconnaissance area, to the right, the ice is mostly obscured by clouds. The eastern part is ice free, and the western part contains mainly young ice in concentrations varying from 0.3 to 0.6. Only the boundary between the ice-free area on the lower left corner and the area of 0.6 concentration (western side) seems to follow the ice outline indicated by the satellite. The clouds over the rest of the area are too numerous to permit positive identification of ice features. The reconnaissance aircraft was in this area about an hour prior to the satellite pass. The wavy lines at the top of the ice reconnaissance indicate that the ice observer found the clouds too thick at that time to permit further ice observation.

Satellite pictures taken during pass 941 on January 26 revealed a fine example of the relation between ice concentration and the prevailing wind. In the upper part of Fig. 7 is a mosaic from that pass showing Chaleur Bay, which lies south of the Gaspé Peninsula (the southern shoreline and several islands have been marked for clarity; the northern coast is partly outlined by fast ice attached to the shore). The lower part of the figure has been based on a chart prepared and distributed by the Canadian Meteorological Service, showing the results of a Canadian ice reconnaissance flight on January 23, 3 days prior to the satellite pictures. The most notable feature of these TIROS II pictures is the low reflectivity of water areas lying to the east and south of land areas, and, conversely, the high reflectivity of those to the west and north. This is seen in three parts of the mosaic: at the lower left, in a line from just below the centre toward the upper right, and at the lower right. Although there is considerable agreement between the Canadian ice information and the satellite pictures, particularly in regard to the fast ice along the southern shore at the far left and to the right, the variable concentration of January 26 contrasts with the more uniform distribution of ice observed on January 23. During the 3 intervening days the winds over this region were persistently west to northwest, as indicated by the wind rose for that period in the lower part of Fig. 7, derived from the meteorological observations at Chatham, N.B., Campbellton, N.B., Mont Joli, P.Q., and Seven Islands, P.Q. It is apparent that the wind has carried the ice away from leeward shores, leaving areas of open water or of ice of low reflectivity. This becomes even more obvious by comparing

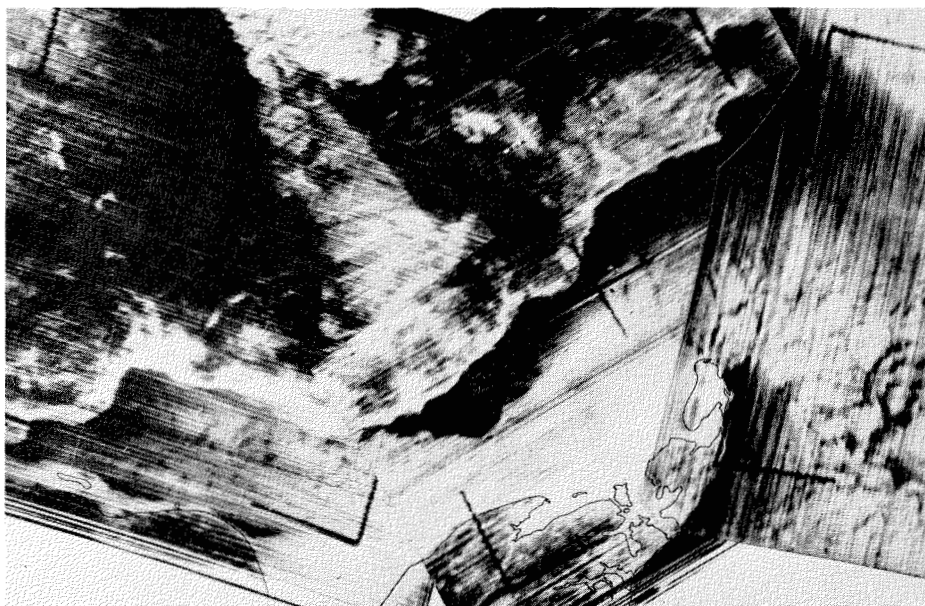


Fig. 7a. TIROS II photographs of Chaleur Bay, from pass 941, January 26, 1961.

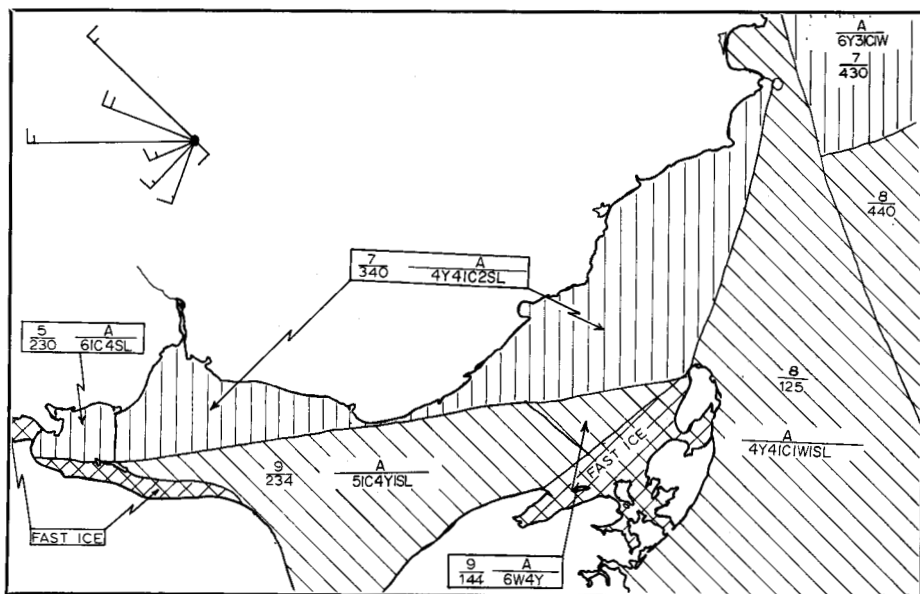
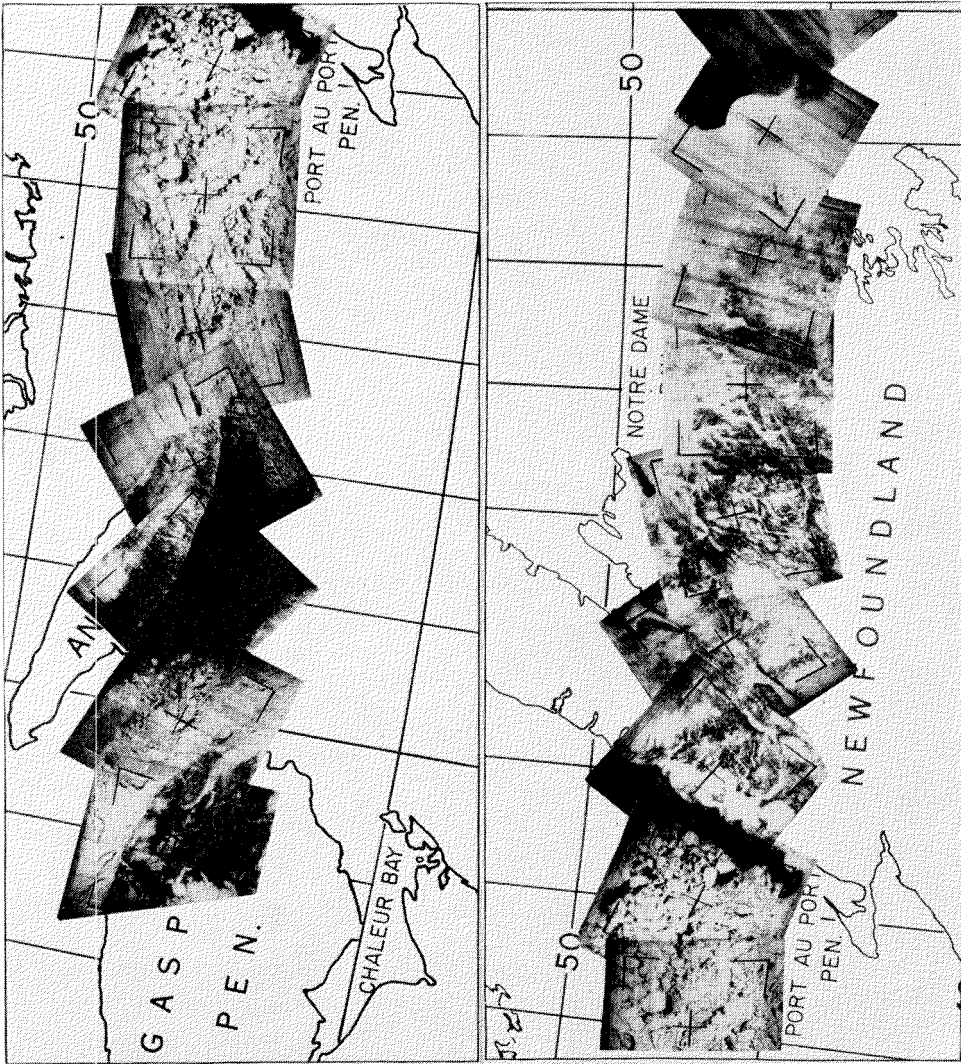


Fig. 7b. Aerial reconnaissance by the Canadian Meteorological Service for January 23, 1961. The satellite photographs show the ice to be packed along the southern and eastern shores even more than indicated by the earlier aerial reconnaissance. The wind rose in the upper left corner is taken from four nearby weather stations for the period January 23 to 26, 1961.

Fig. 8. Composite picture of TIROS II photographs from pass 1763, March 23, 1961, extending from Gaspé Peninsula eastward across the Gulf of St. Lawrence and Newfoundland to the Atlantic. The lower section is the eastward extension of the upper; the part near the Newfoundland west coast is repeated in the lower section.



the ice in Chaleur Bay with that in the gulf at the far right; with no impeding shore in the latter area to block the motion of the wind-driven ice, the concentration is less there.

The best overall sequence of satellite ice photographs obtained in this study was that taken on pass 1763 on March 23. Fig. 8 is a composite picture of the photographs from that pass; in order to present greater detail it has been divided into two sections, the upper part showing the Gulf of St. Lawrence from Gaspé Peninsula to the Newfoundland coast and the lower part showing the extension across Newfoundland into the Atlantic Ocean. No clouds are present except some thin cirrus at the extreme right.

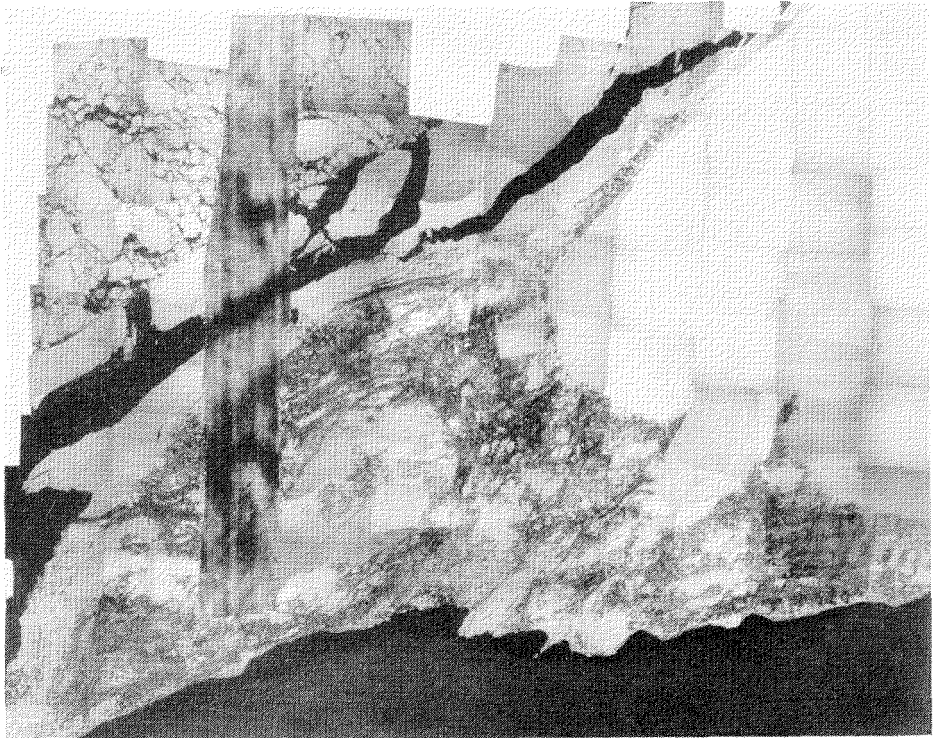


Fig. 9. Mosaic of aircraft photographs over Port au Port Peninsula, March 24, 1961. The dimensions are about 20 by 25 miles.

The better illumination in March and the breaking of the winter ice have resulted in a more striking set of pictures. Over most of the gulf there is either open water or fields of broken ice. Along the north coast of Anticosti Island the ice is still solid, but large cracks show near the eastern tip of the island. Between Anticosti Island and Newfoundland is a particularly interesting field of floes, ranging in size from barely distinguishable dots only a few hundred yards in diameter up to giant floes nearly 10 miles across.

Rivers and lakes of Newfoundland are frozen. The ice in the Atlantic appears to be solid along the Newfoundland coast with a sharp edge, beyond which are belts and patches barely discernible below the cirrus clouds.

On March 24 U.S. Navy Patrol Squadron 23 conducted a photographic reconnaissance in the vicinity of the Port au Port Peninsula, timed to coincide with the passage of TIROS II. Circumstances permitted photographs to be taken of the area on two successive passes, 101 minutes apart. Fig. 9 is a mosaic of the aircraft pictures, taken from 10,000 feet. Port au Port Bay is covered with solid ice; St. Georges Bay to the south is ice free; and the gulf to the north contains a flaw lead along the north coast of the peninsula

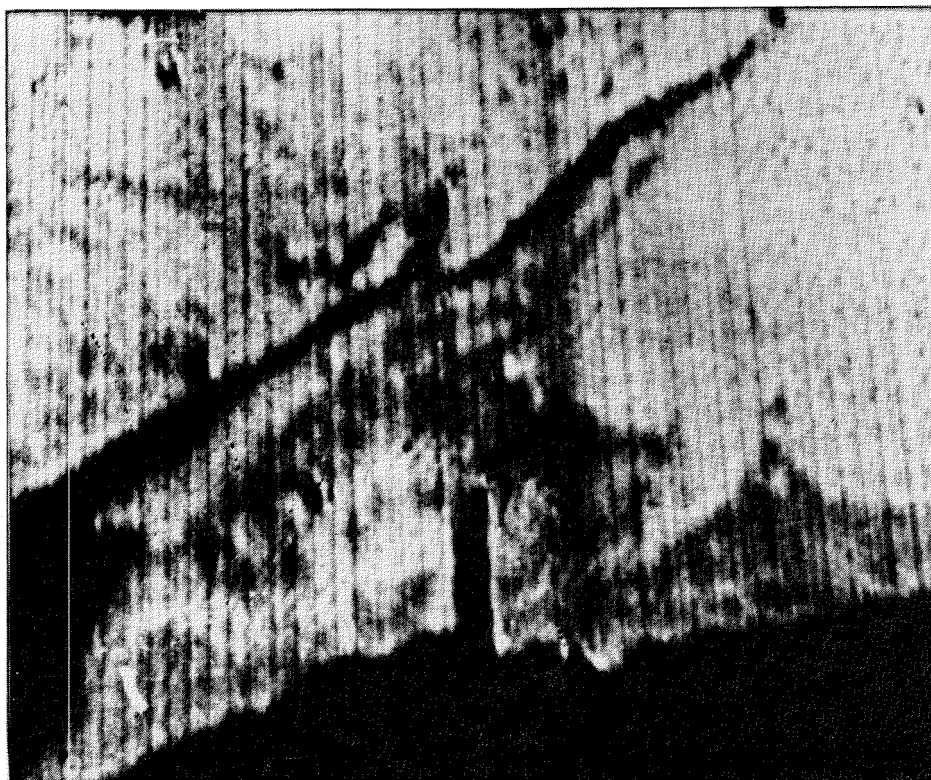


Fig. 10. Enlargement of a part of a TIROS II pass 1777 photograph, showing the same area as seen in Fig. 9. The vertical dark line is a fiducial mark on the vidicon tube.

and broken ice consisting of floes up to giant size. Malfunction of the aircraft camera resulted in the loss of one strip of pictures; Fig. 9 was patched with a part of Fig. 10 to fill the missing section (left of centre). Fig. 10 is an enlargement taken from pass 1777, showing the same area. The aircraft was making its eighth photographic run (the missing series) at the time this satellite picture was taken. Most of the larger features seen in Fig. 9 are easily distinguished: some of the floes that are surrounded by more than

an eighth of a mile of open water (the limit of resolution); the flaw lead; and the fast ice connecting Red Island (far left) with the peninsula. Fig. 11, from pass 1778, taken 101 minutes later, is almost identical, but changes in the relative positions of individual floes near the flaw lead can be distinguished. It has been suggested that the movement of ice between passes 1777 and 1778 may only be the consequence of changing solar illumination, different camera orientation, different scan line orientation, and photographic effects. Only the last two of these are deemed of possible consequence, however, because the solar illumination has not changed markedly in this case, and the photographs have been rectified geometrically. On the assumption that the differences between Figs. 10 and 11 are genuine, it is found that the flaw lead increased in width from 1.0 mile to 1.75 miles near the western end, and from 0.5 mile to 0.75 mile in the central part. It should be noted that the surface wind was easterly 5 to 10 knots during the preceding 24 hours.

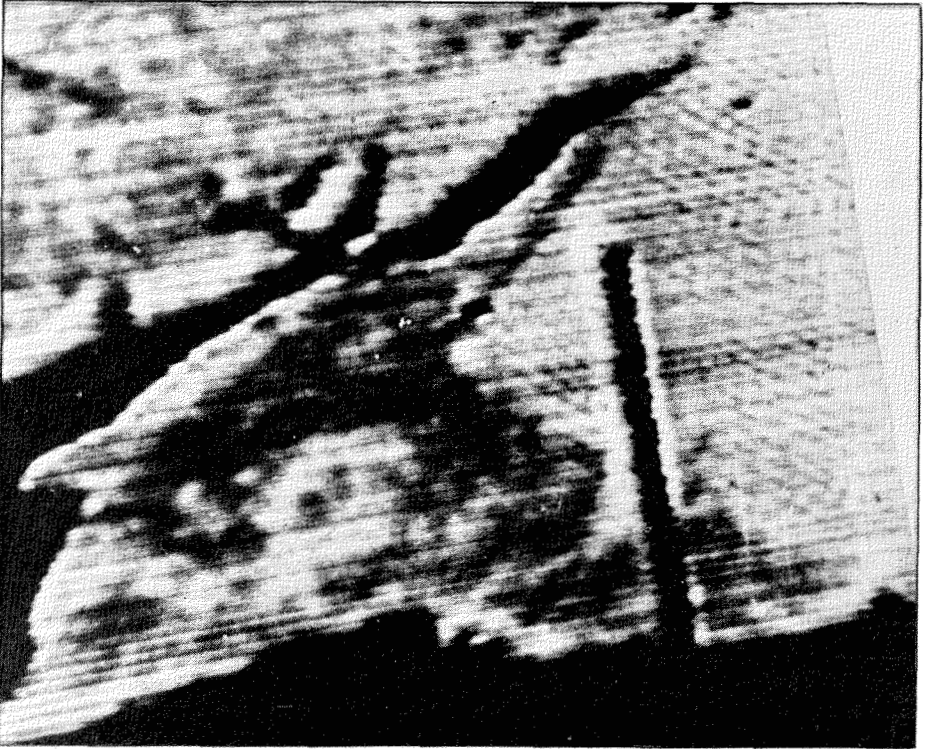


Fig. 11. Enlargement of a part of a TIROS II pass 1778 photograph, showing the same area as seen in Figs. 9 and 10. The vertical dark line is a fiducial mark on the vidicon tube.

The displacement of the ice near the flaw lead was measured in two ways. First, the change was measured by a scale, after checking for distortion by measuring distances between several reference points of known

geographical position. In addition, the two photographs were treated as stereo pairs and, using a time-lapse sequence and parallax-displacement technique, the speed and direction of movement of the ice was noted. This technique was also applied to overlapping aircraft photographs as a check, using pictures from adjacent runs. Using this method, a moving object will appear displaced vertically in relation to a fixed object, and tilted in the direction of movement. The resulting measurements from satellite and aircraft photographs were in very close agreement. The evidence is apparently in favour of genuine movements of ice of about the order mentioned above.

Fig. 12 is shown to illustrate more positively the changes in ice conditions that occur over long and over short periods. The area is that of the estuary of the St. Lawrence River: Gaspé Peninsula is along the bottom of the photographs; Manicouagan Peninsula, surrounded by fast ice, is readily identifiable near the centres of the pictures. Picture 12a, taken on January 26 during the same pass from which the pictures of Chaleur Bay (Fig. 7) were taken, again shows the northern shore to be relatively free of ice, whereas the concentration of ice is greatest toward the southern shore, presumably a consequence of the west and northwest winds that had prevailed in this area for the 3 days prior to this observation. The existence of more open water in the centre of the picture may be a reflection of the wind or of the water currents. By close inspection belts and patches can be distinguished within the ice, particularly in the lower left side of the picture, despite the heavy concentration found there.

Picture 12b was taken two months later, and reveals the changes that have taken place, both in the estuary and along the shore. Fast ice, particularly around Manicouagan Peninsula and to the southwest, extends farther into the estuary; this itself now contains ice floes of all sizes, including giant floes. Picture 12c was taken 24 hours later, and from almost the same angle; the reader can see many small and large scale changes, including a suggestion of westerly movement. The changes from January to March were from a state of young ice, not yet covering the estuary and gulf, to a condition of breaking up of the solid ice of the intervening period. The 24-hour change is mainly in position, caused by wind and current, although the lower left corner shows the destruction of an ice field in that short time. Individual floes can, in many cases, be identified in each of the March photographs. A field of belts and patches that appears at the far right in Fig. 12c is not seen at all in Fig. 12b.

Conclusion

A part of the available TIROS II photographs have been shown here to illustrate the capacity of a satellite to conduct ice reconnaissance. The simultaneous use of aircraft visual and photographic observations has given support to some interpretations. It has been found that many details of the ice can be distinguished, such as type of ice, amount, and presence of leads

and cracks. In addition, one may often differentiate between clouds and ice; however, in some cases, as in Fig. 6, where clouds of a certain type and amount were present, considerable difficulty may be encountered. Nevertheless, ice and clouds usually have different appearances, so that photographs lend themselves to analysis by a skilled interpreter. When the ice begins to break, the contrast between sea and ice leaves little doubt about the state of the ice. On the other hand, young ice is more difficult to differentiate from open water, although even here the interpreter may use his talent fruitfully.

Fig. 12a-c. TIROS II photographs of the western part of the estuary of the St. Lawrence River; a and b were taken 2 months apart, on January 26 and March 26, 1961, respectively; b and c were taken 24 hours apart, on March 26 and 27, 1961, respectively.

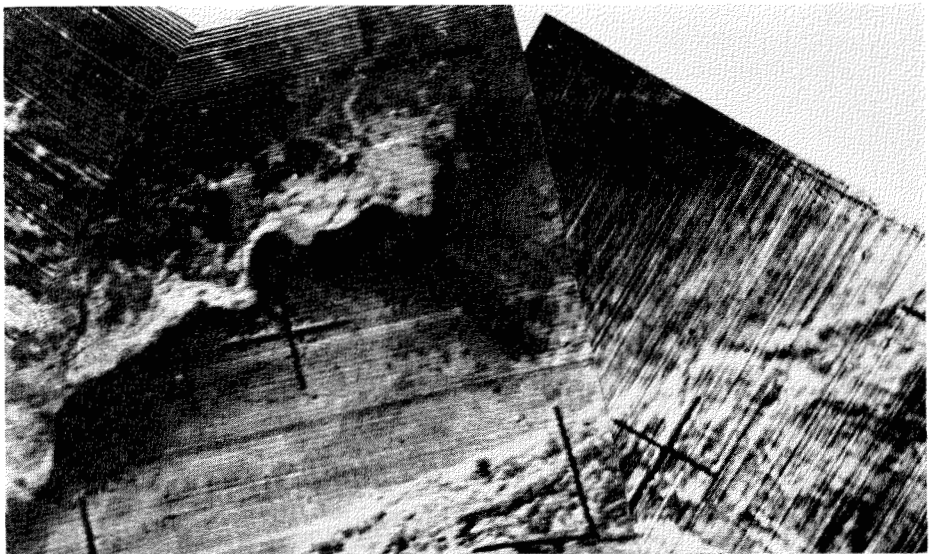


Fig. 12a. Orbit 941, January 26, 1961.

The present study has been confined to the southern fringe of winter sea-ice by the 48-degree inclination of the orbit of the TIROS II satellite. In addition, the exclusive use of the narrow-angle camera, necessitated by technical difficulties, limited the coverage. Although the excellent detail of the photographs has been illuminating, the far greater coverage of a wide-angle camera (105° in the diagonal for TIROS II) is a requisite for extensive reconnaissance. Introduction of polar orbiting satellites will allow complete examination of the arctic and antarctic water areas, and it will be possible to proceed to the task for which these instruments are excellently suited. Whereas the TIROS series of satellites permits only a brief glimpse of the potential in this field and can therefore serve only in an experimental

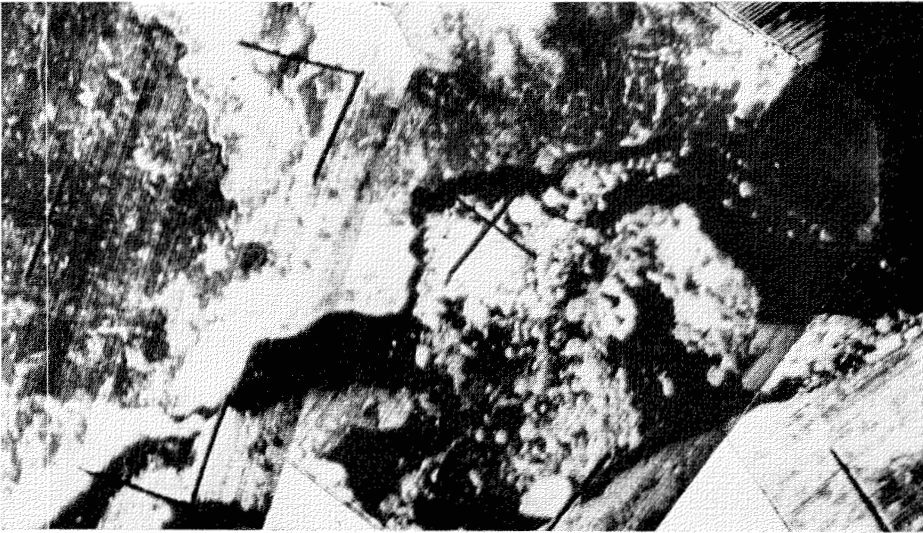


Fig. 12b. Orbit 1807, March 26, 1961.

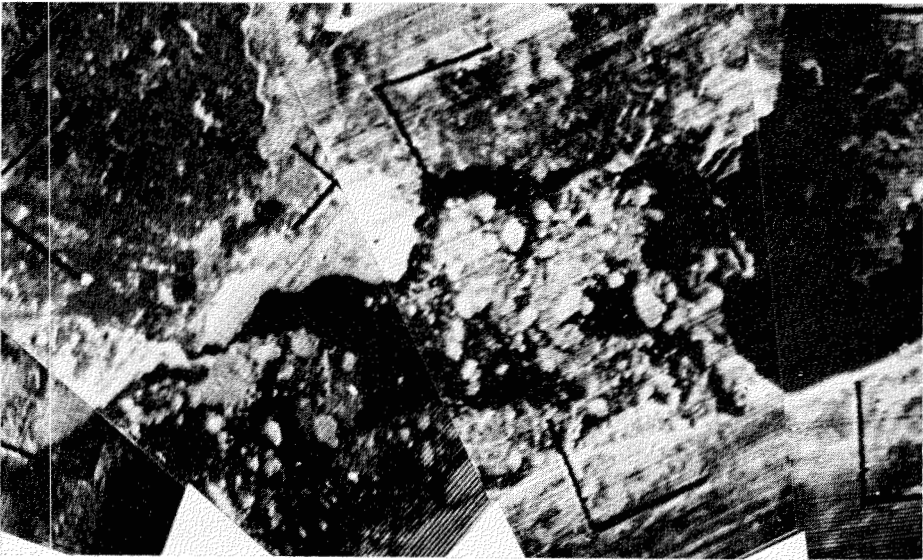


Fig. 12c. Orbit 1821, March 27, 1961.

capacity, future satellites will be useful in the gathering of ice statistics, the mapping of ice for use on an operational basis, and the study of ocean currents at high latitudes. Although conventional ice reconnaissance will continue in tasks for which the satellite is limited, such as observations of fine detail and in areas of persistent cloudiness, satellites offer an opportunity

for surveys on a scale not otherwise feasible. The satellites and the photographs will be available: the NIMBUS series of meteorological satellites will carry television cameras and infrared sensing equipment in a quasi-polar orbit of 83-degree inclination for daily coverage of the entire arctic and antarctic regions. It is seldom that a revolution can be effected with so little effort by the participants as that which can be expected in the field of ice observation and surveillance.

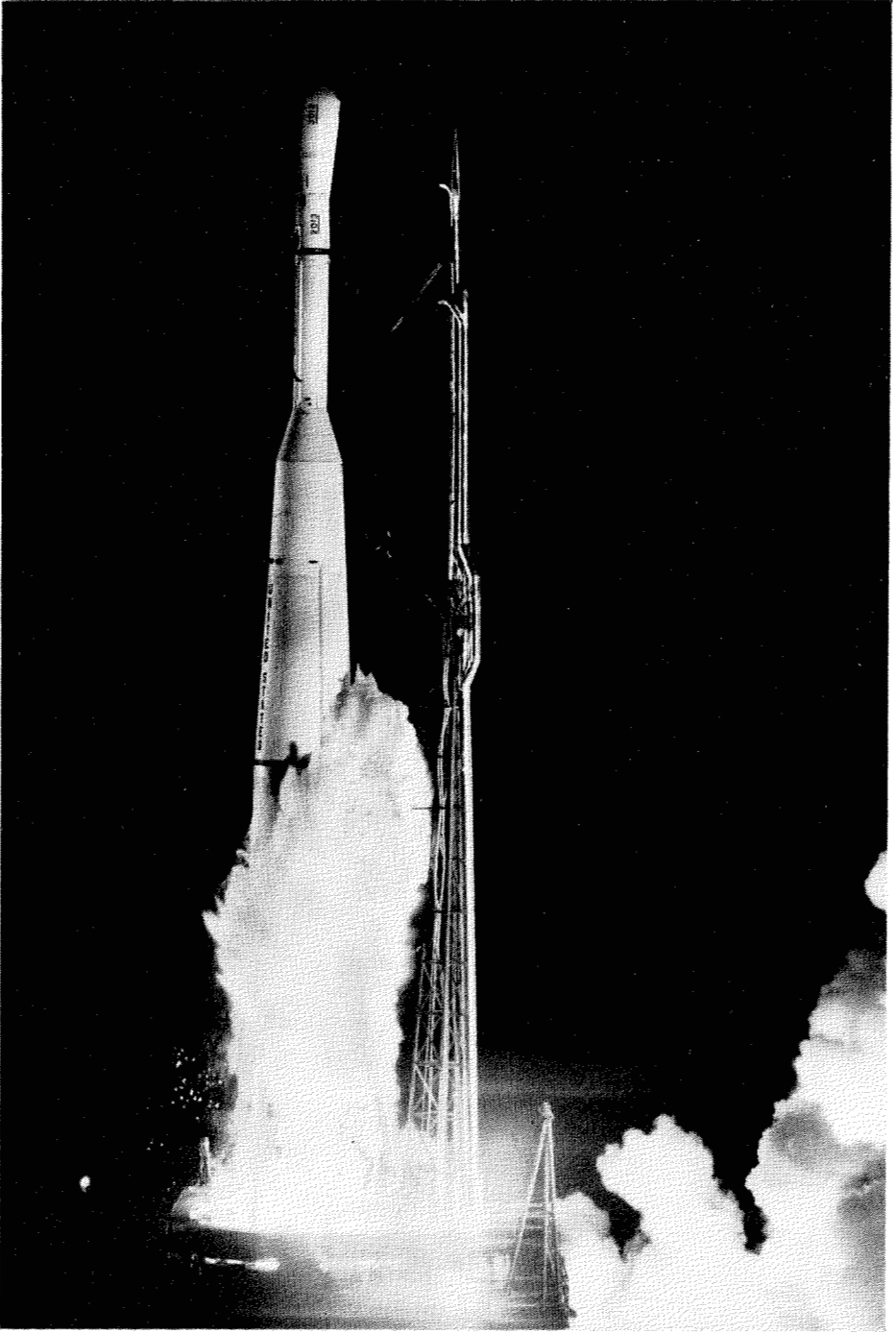
Acknowledgements

The authors are indebted to many individuals and groups for assistance in this experiment. We are particularly grateful to the personnel of U.S. Navy Patrol Squadron 23 who conducted the aerial reconnaissance, to Gilbert Jager of the U.S. Weather Bureau for his part in the programming of the TIROS II pictures, to personnel of the Photogrammetry Branch, Nautical Chart Division, U.S. Navy Hydrographic Office for the preparation of parts of the photographic material, and to D. M. Mercer of the U.S. Weather Bureau for his assistance in the preparation of the figures. We also wish to thank the Canadian Meteorological Service for the use of their ice reconnaissance charts.

The work of D. Q. Wark and R. W. Popham was supported in part by the National Aeronautics and Space Administration.

References

- U.S. Navy Hydrographic Office 1952. A functional glossary of ice terminology, H. O. Pub. No. 609, Washington, D.C.
- Wark, D. Q. and R. W. Popham. 1960. TIROS I observations of ice in the Gulf of St. Lawrence, *Monthly Weather Review*, 88:182.



National Aeronautics and Space Administration Photo

Launching of the 280-pound meteorological satellite *Tiros II* on a three-stage Delta rocket at Cape Canaveral, Florida, on November 23, 1960.