ARCTIC
VOL. 33 No. 2 (JUNE 1980), P. 280-291

Orbital Sensing of Mackenzie Bay Ice Dynamics

B. DEY[1]

ABSTRACT. Satellite images are a useful tool in the study of sea ice dsnamics. The results of studies using satellite images of Mackenzie Bay during the break-up and freeze-up periods are presented in maps and tables. These indicate important temporal variations in the processes of bay ice break-up and freeze-up, Though the Mackenzie Bay break-up proceeds from the south and from the north, the southern melt rate is faster because of an influx of warm water from the Mackenzie River. The freeze-up proceeds from south to north, i.e., from the fresh water area to the saline water area of the bay. The study of Mackenzie Bay ice dynamics is important because of the barge traffic through the Mackenzie River and also because of offshore drilling activities in the Beaufort Sea.

RÉSUMÉ. Les images prises par satellite sont un outil utile pour l'étude de la dynamique des glaces de mer. Des cartes et des tableux illustrent les resultats des études faites à partir des images orbitales, cela à l'époque du degél et du gel. Ils indiquent des variations importantes temporaires dans les processus du degél et du gel de la glace de baie. Bien que le degél de la baie du Mackenzie se rèalise à pârtir du sud et du nord, la fusion méridionale êst plus rapide, à cause d'un apport d'eau "chaude" venant du fleuve Mackenzie. Le gel se rèalise du sud au nord, de la region à l'eau douce vers celle à eau salée de la baie. L'étude de la dynamique de la glace de la baie du Mackenzie est importante à cause de la circulation des barges sur le fleuve Mackenzie et aussi à cause des activités de forage en mer de Beaufort.
Traduit par Alain de Vendegies, Aquitaine Company of Canada Ltd.

INTRODUCTION

Water transportation has always been the chief method of transporting goods and services to the Mackenzie area. For marine transportation throug Mackenzie Bay, information about the break-up and freeze-up behavior of Mackenzie Bay ice and Mackenzie River ice is essential. Such information is important not only for summer barge traffic through the Mackenzie River, but also for the construction of artificial islands for oil exploration and for the study of marine biological activity. In addition, the Mackenzie Basin snowmelt, the river break-up and the subsequent Mackenzie Bay ice deformation are very significant events for climatologists, hyrologists and marine scientists. Valuable information about ice dynamics in Mackenzie Bay can be derived from satellite images. This paper demonstrates the applications of orbital sensing for mapping Mackenzie Bay ice dynamics (Fig. 1).

Studies related to snow and ice dynamics in the Arctic have been augmented with the launch of the satellite TIROS in April 1960. In the early stages, the results were discouraging due to the limitations of the sensors and poor ground resolution. However, the recent satellites, particularly Landsat and NOAA, have proved to be very useful for sea ice study (McClain, 1974; Wiesnet, 1974; Barnes, 1975; Marko, 1975; Ramseier *et al.*, 1975; Dey, 1978; Dey *et al.*, 1979a).

[1]Department of Geography, University of Saskatchewan, Saskatoon, Canada S7N 0W0

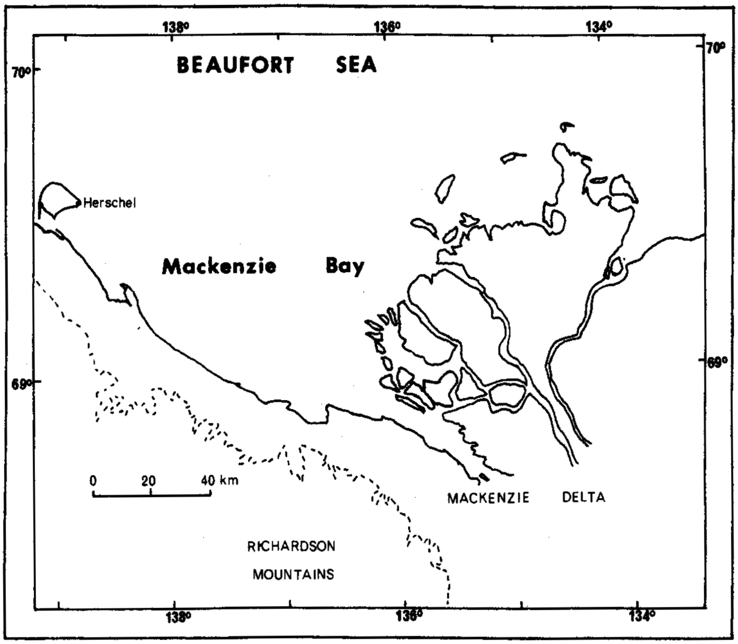

FIG. 1. The study area.

DATA AND METHODOLOGY

Landsat and NOAA images of Mackenzie Bay for the period 1973 to 1977 were used in this study of ice dynamics. In addition, sea ice charts from Ice Climatology and Applications Division, Atmospheric Environment Service (A.E.S.), Ottawa were used for the period 1970 to 1972. The parameters of Landsat and NOAA satellites are given in Table 1. Landsat-1 (now replaced by Landsat-3) and Landsat-2 (inoperative as of early 1980) circle the globe every 103 minutes at an altitude of 917 km. The sensors of the spacecraft view a strip of earth 185 km wide. Surface coverage of the earth proceeds westward with some overlap so that the globe is covered once every 18 days. The National Oceanic and Atmospheric Administration satellites (NOAA-5, now replaced by TIROS-N and NOAA-6) orbit the globe every 115 minutes at an altitude of about 1500 km and image a swath 2350 km wide. Each satellite proceeds westward by 29 degrees of longitude on each successive orbit, providing complete global coverage over a 24-hour period (Irwin, 1977).

Simple photo interpretation techniques were used to map ice conditions on Mackenzie Bay because the techniques are straightforward and do not necessitate the use of elaborate equipment. Both Landsat and NOAA images were in glossy prints. In both Landsat and NOAA images, the open area of Mackenzie Bay appeared black to dark grey against the white background of ice/snow covered areas. The individual bands (4 to 7) of Landsat - MSS (Multispectral Scanner) are useful in distinguishing between thin ice and open water.

TABLE 1: Satellite Parameters

Satellites	Spectral Bands	Ground Resolution	Scale of Standard Product
Landsat 1 & 2:	RBV: .45-.57 micron		
18-day cycle;	(Band 1)	80 meters	1:1,000,000
near polar orbit	.58-.68 micron		
(N. B.: Landsat 1 became	(Band 2)		
inoperative as of Jan. 78;	.69-.83 micron		
and Landsat-3 was launched	(Band 3)		
in February 1978. Landsat 2			
became inoperative as of	MSS: .5-7 micron		
early 1980.)	(Band 4)		
	.6-.7 micron		
	(Band 5)		
	.7-.8 micron		
	(Band 6)		
	.8-1.1 micron		
	(Band 7)		
NOAA-5	VHRR: .6-.75 micron	.9-1.9km	Variable
(N.B.: NOAA-5 is	10.5-12.5 microns	.9-1.9km	1:6,000,000 (Approx.)
replaced by TIROS-N	SR: .52-.73 micron	3.7km	
and NOAA-6)	.50-.94 micron	3.7km	
1-day cycle for VHRR;	10.5-12.5 microns	7.4km	
polar orbit			

RBV — Return Beam Vidicon; MSS — Multispectral scanner; VHRR — Very High Resolution Radiometer; SR — Scanning Radiometer.

After: Dey *et al.* (1978).

REMOTE SENSING OF THE MACKENZIE BAY ICE DYNAMICS

The break-up in Mackenzie Bay, especially in the south, is associated with the onset of snowmelt in the Mackenzie Basin and the subsequent Mackenzie River ice break-up and snowmelt runoff.

Snowmelt and Runoff in the Mackenzie Basin

The snowmelt starts in the southeastern part of the basin and proceeds towards north and northwest. The lower basin is snowfree by the end of May or early June, but in mountainous regions on the western side of the basin snow remains until July (Dey*et al.*, 1979b; 1979c). Snowcover depletion and runoff have a direct impact on the Mackenzie River ice break-up because of heat input from snowmelt water. The lower Mackenzie River is normally ice free by the end of May or early June (Dey *et al.*, 1977; MacKay, 1965). Runoff from the river flows out over the bay, flooding a very large area, while snowmelt continues in coastal regions and in higher elevations. The physical and biological environments of the bay are significantly affected by the early summer heat transport of the Mackenzie runoff. From a physical point of view, the large heat transport of warm Mackenzie water is an important factor

FIG. 2. Landsat (Band 7) image, 20 June 1973. It shows the break-up of landfast ice by Mackenzie River outflow.

in ice disintegration along the dela perimeter and in southern Mackenzie Bay. Moreover, from a biological point of view, the bay's aquatic life is partly dependent on the influx of warm Mackenzie water during early break-up periods. It should be noted that the snowmelt runoff event is by far the most dynamic and impressive hydrologic event in the Mackenzie Basin.

Mackenzie Bay Ice Dynamics

During winter most of Mackenzie Bay is covered with landfast ice. The only exceptional area is the northwest corner near Herschel Island which is part of the shear zone (Wadhams, 1976). The fast ice is a continuous sheet of seasonal ice extending out from the shore to the 18-20 m isobath line

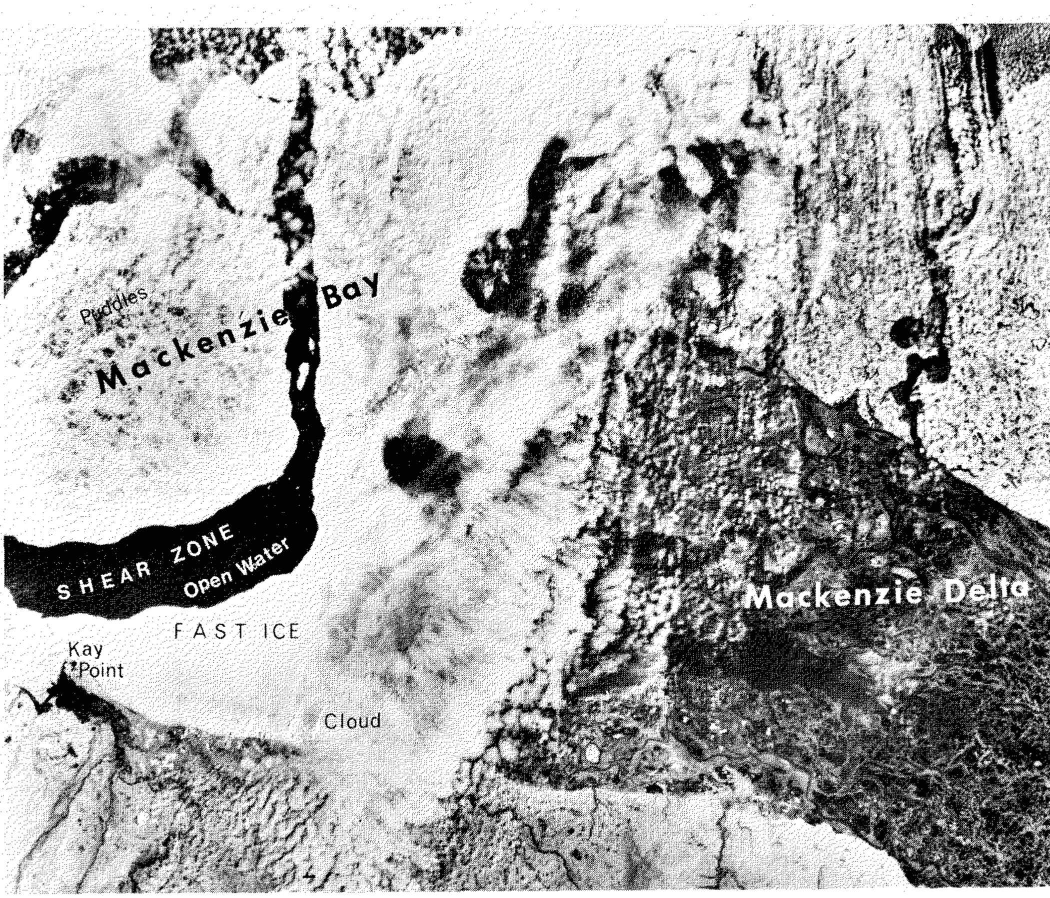

FIG. 3. Landsat (Band 7) image, 20 June 1975. It shows the break-up of landfast ice from the shear zone towards the Mackenzie Delta.

(Stringer, 1974; Cooper, 1975). Fast ice includes grounded pressure ridges or ice fragments. Shear zones, also comprised of seasonal ice, cover the area between the edges of fast ice and polar pack ice. Throughout the winter leads develop and refreeze in the Beaufort Sea. However, in late winter and early spring the bay becomes active with the development of large leads. In spring, leads expand into polynyas and the areas of open water increases with the input of more solar radiation.

The break-up in the Mackenzie Bay is an interesting phenomenon because it occurs from two directions: (a) the outflow from the Mackenzie River breaks the landfast ice from the delta region northwards toward the northern part of the bay (Fig. 2); and (b) the break-up from the shear zone proceeds at a very slow rate toward the south into the delta region (Fig. 3).

First flow in the Mackenzie River and in the deltas and estuaries occurs well before sea ice break-up and is commonly over bottomfast winter ice. This ice inhibits bad scour during early flooding (Fig. 43. Sediments carried by the streams during the break-up period are deposited on top of the ice. The

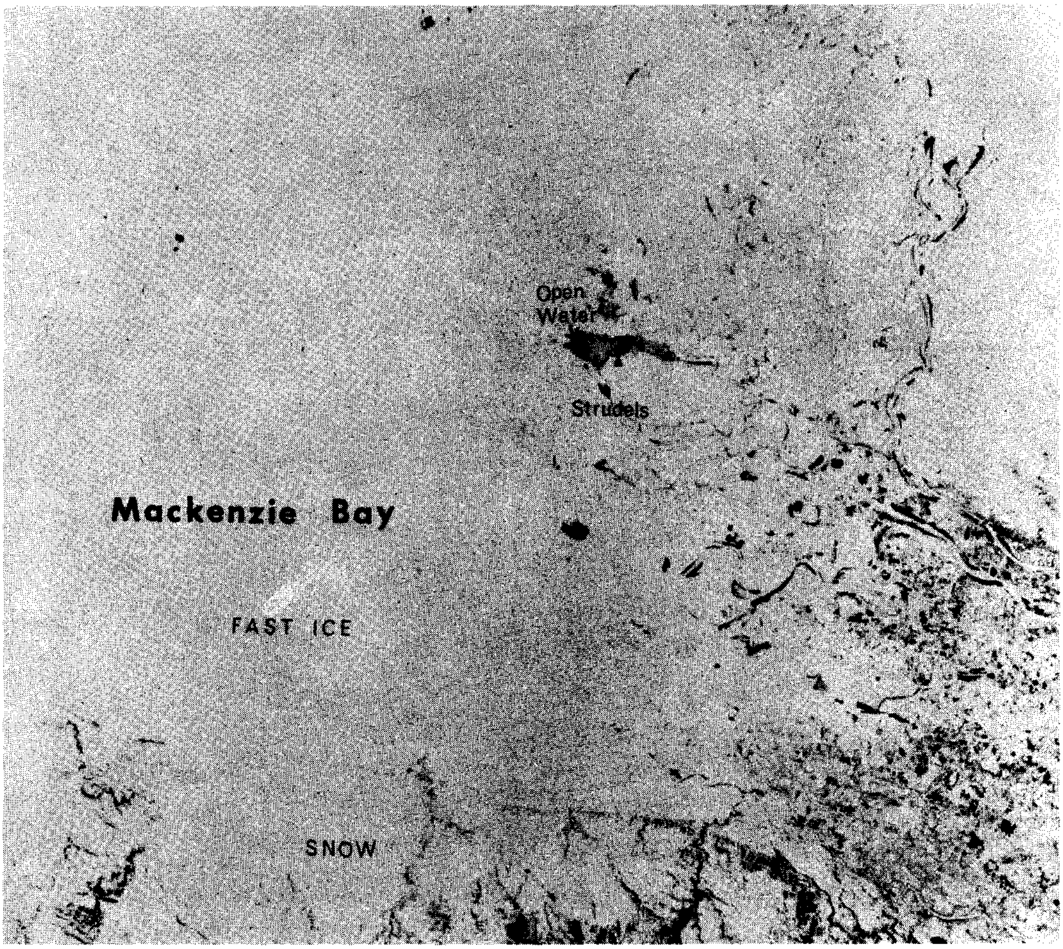

FIG. 4. Landsat (Band 6) image, 15 May 1975. It shows flooding over landfast ice by Mackenzie River outflow.

streams and sediments drain holes (strudels) in the bay ice (Reimnitz *et al.*, 1974). Once the water drains through the holes, the ice is lifted vertically (Kane *et al.*, 1975). The sediments and water draining through the holes contribute to deterioration of the bay ice. Thus the warm water and silt load carried by the river accelerate the rate of ablation of bay ice and the open water area expands from the delta region toward northern Mackenzie Bay (Fig. 5). The open water surface in Mackenzie Bay absorbs several times as much solar radiation as is absorbed by a snow/ice surface (Gill, 1974), and thereby accelerates the melting process. The bridge of ice in the center of the bay (Fig. 5), between the open water on its northern and southern flanks, eventually melts (Fig. 6) as a result of an increase in the outflow from the Mackenzie River, and because of southerly winds and increases in temperature.

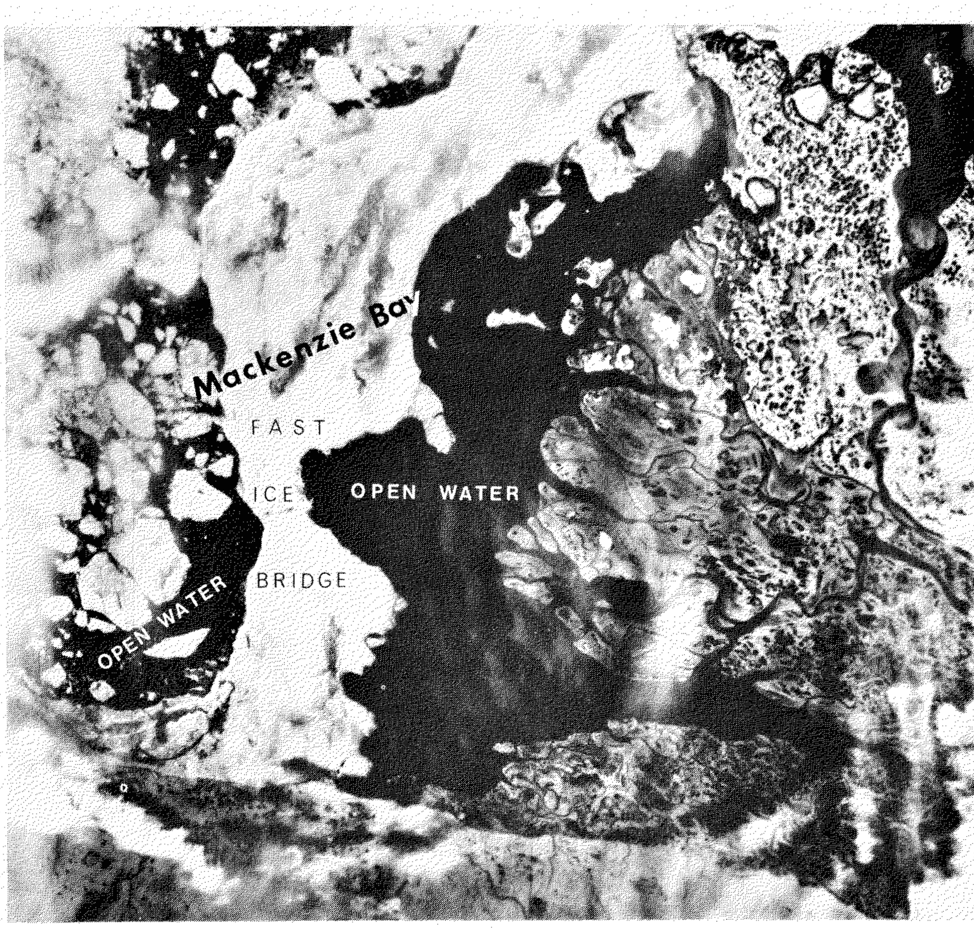

FIG. 5. Landsat (Band 7) image, 21 June 1973. It shows expansion of open water, and an ice bridge between open water on its northern and southern flanks.

The open water season in Mackenzie Bay and the southern Beaufort Sea may last up to 120 days, or it may not occur at all if northerly winds drive polar pack ice down against the coast. In the fall, due to low sunlight and decreasing temperatures, ice starts forming in the fresh Mackenzie water rather than in the saline water of the northern bay and Beaufort Sea. Freeze-up recommences in early October in the delta areas and from here young fast ice spreads seaward. By late October the bay is normally ice-covered (Fig. 7). After complete ice cover is achieved, new leads may give indication of activity in the region. During winter, satellite thermal infrared images are necessary for monitoring winter ice dynamics (Dey, in press).

VARIATIONS OF MACKENZIE BAY ICE BREAK-UP AND FREEZE-UP (1970-1977)

Ice Forecasting Central, A.E.S. at Ottawa prepares detailed maps indicating ice conditions for shipping routes in Mackenzie Bay as well as in

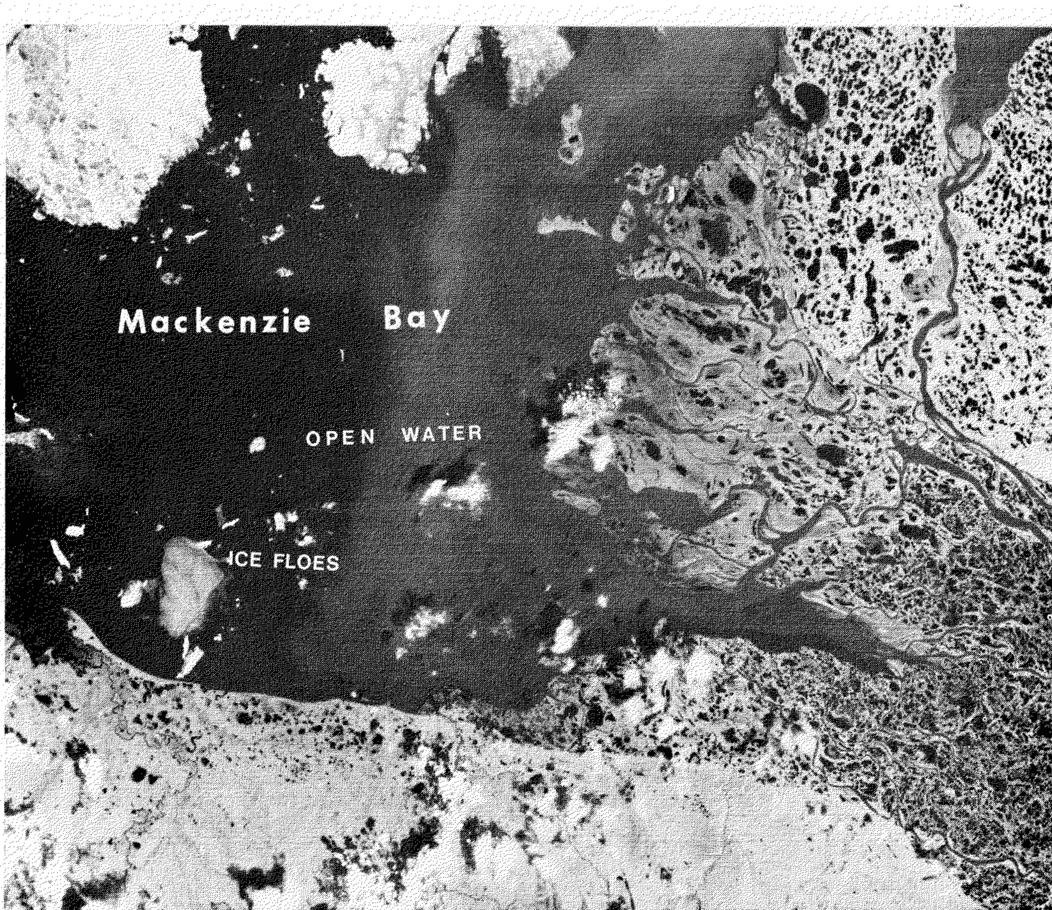

FIG. 6. Landsat (Band 6) image, 8 July 1975. It shows the melting of landfast ice and expansion of open water towards Beaufort Sea.

the rest of the Canadian Arctic waterways. In this study data for 1970-77 break-up and freeze-up are presented in Figure 8 and Table 2 respectively. These break-up data indicate the semi-monthly distribution of ice and open water from June to August, i.e., 15 June, 30 June, 5 July, 31 July and 15 August.

Areal and Temporal Variations of Break-up

An overview of Figure 8 indicates that the rates of break-up were fast in 1977 and 1972, and slow in 1974 and 1976. In both 1977 and 1972 the Mackenzie Bay region had large areas of open water by June 15 and the bay was completely ice-free by 15 July; and similar fast ice break-up was also noted in 1975. On the other hand, in the 1974 and 1976 break-up seasons, the areas of open water were still significantly small by 15 June. Moreover, the bay was not completely ice-free until early August. In eight summer seasons there were time differences of three to four weeks in complete break-up of

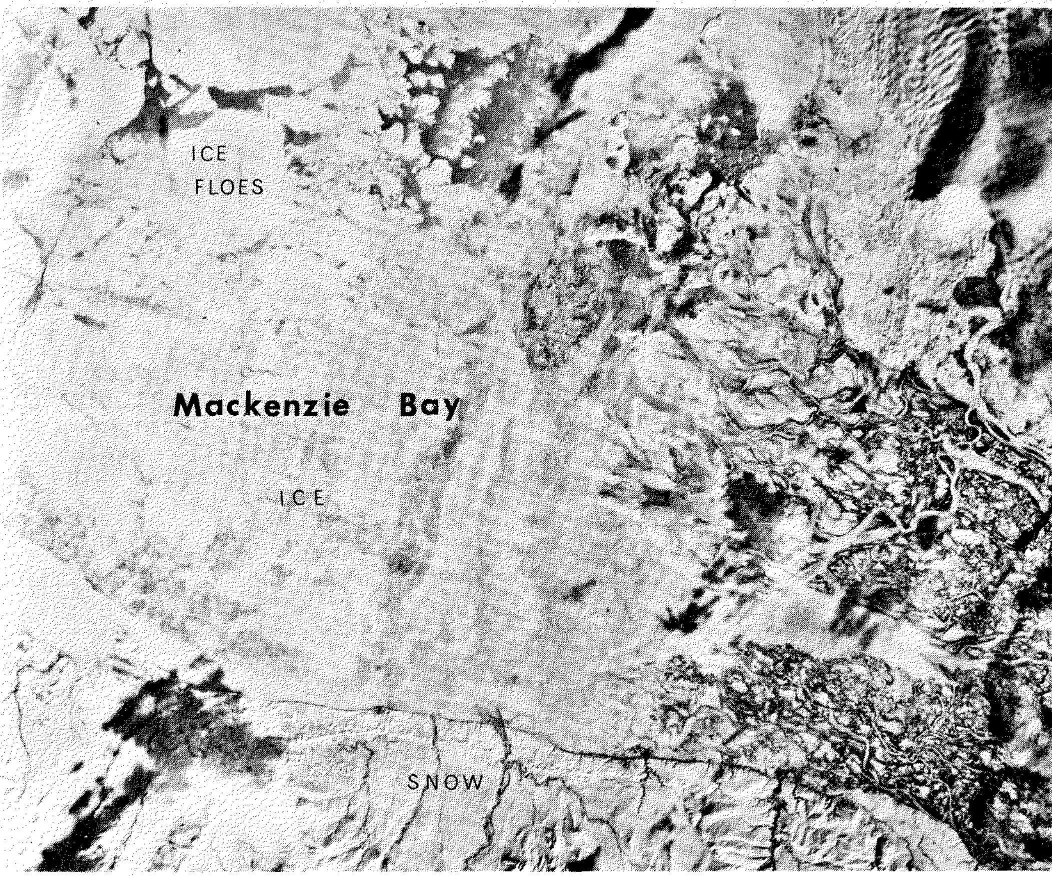

FIG. 7. Landsat (Band 6) image, 20 October 1974. It shows the Mackenzie Bay is mostly covered with landfast ice.

bay ice. The areal break-up pattern was more or less consistent in spite of temporal variations.

Temporal Variations of Freeze-up

The freeze-up of bay ice spreads from the fresh water area of the Mackenzie Delta northward to the saline water area of the Beaufort Sea. Table 2 indicates the temporal variations of freeze-up in the Mackenzie Bay. The early and late freeze-ups were recorded in 1974 (October 1) and 1975 (October 17) respectively. The early and late freeze-ups were related to the early or late arrival of cold northerly winds.

Indeed, the summer of 1974 had the worst ice conditions on record (Herlinveaux, 1975), meaning that the open water season was short and the area of open water in the Beaufort Sea small. During the summer of 1974 the winds were predominantly northerly which kept the ice near the shore.

During the study period the time difference between early and late freeze-up varied between two and three weeks, which was less than the time difference between early and late break-up in the bay.

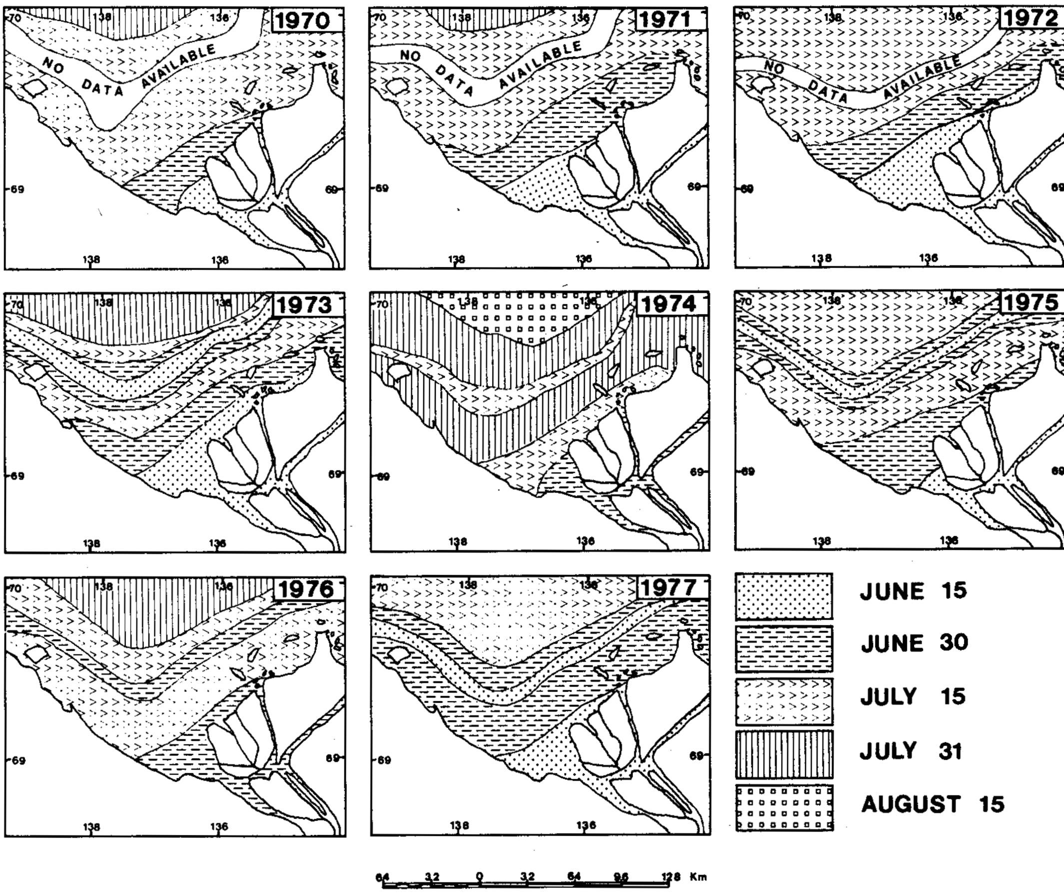

FIG. 8. Progress of sea-ice break-up in Mackenzie Bay on June 15, June 30, July 15, July 31, and August 15, from 1970 to 1977. (Source: Landsat and NOAA images; and Sea Ice Charts, Ice Climatology Section, Atmospheric Environment Service, Canada.)

TABLE 2: Mackenzie Bay Ice Freeze-up Dates, 1970-1977.

Year	Freeze-up Dates
1970	2 October
1971	15 October
1972	22 October
1973	8 October
1974	1 October
1975	17 October
1976	15 October
1977	21 October

Source: Ice Climatology and Applications Division, A.E.S., Ottawa.

CONCLUSIONS

A study of satellite images reveals the patterns of ice deformation processes in the Mackenzie Bay. The bay ice break-up proceeds from the south as well as from the north, the former being more important in the break-up process. The study reveals significant temporal variations of ice break-up and freeze-up in the bay region. In the bay, 1974 was a year of late break-up and early freeze-up, and therefore a summer season unfavourable for navigation and drilling operations. On the contrary, 1977 was a good year for navigation because of early break-up and late freeze-up. The study reveals tha satellite images are a valuable tool for studying meso-scale ice dynamics in the Mackenzie Bay, despite periodic obscuration by clouds.

With satellite images it has been possible to monitor snowcover depletion, to measure the extent of flooding over ice by fresh water from the Mackenzie River, to monitor break-up and freeze-up patterns of the Mackenzie ice, and also to observe the growth and disappearance of leads and polynyas. The best results in mapping Mackenzie Bay ice break-up were obtained by integrating Landsat and NOAA images, and A.E.S. sea ice charts.

Finally, the application of satellite sensing is the most economical way of monitoring and mapping sea ice dynamics, not only in the Mackenzie Bay area but throughout the Canadian Arctic.

ACKNOWLEDGEMENTS

The author is grateful to Professor R. Rees, Department of Geography, University of Saskatchewan, Saskatoon for editing the original manuscript and to the University of Saskatchewan for financial assistance. Thanks are also due to Mr. Fred Geddes, Ice Climatology and Applications Division, A.E.S., Ottawa for providing sea ice charts.

REFERENCES

BARNES, J. C. 1975. The application of ERTS imagery to monitoring arctic sea ice, Supplemental Report. Concord, Mass: Environmental Research and Technology Inc. ERT Document No. 0408-S. 51pp.

COOPER, P. F. 1975. Movement and deformation of the landfast ice of the southern Beaufort Sea. Victoria: Canada Department of Environment. Beaufort Sea Project Report No. 37.

DEY, B., MOORE, H. and GREGORY, A. F. 1977. The use of satellite imagery for monitoring ice break-up along the Mackenzie River, N.W.T. Arctic 30 (4): 234-242.

DEY, B. 1978. Use of Landsat and NOAA imagery for mapping deformation and movement of Baffin Bay ice. Proceedings of Fifth Canadian Symposium on Remote Sensing, Victoria,B.C., August 1978. Ottawa: Canadian Aeronautic and Space Institute. p. 200-208.

———. 1980. In press. Applications of satellite thermal infrared images for monitoring North Water during the periods of polar darkness. Journal of Glaciology.

———, GREGORY, A. F. and MOORE, H. 1978. Towards the development of engineering applications for orbital remote sensing in the cold regions of Canada. Unpublished research report no. 78-4, Gregory Geoscience Limited, Ottawa. Prepared for National Research Council of Canada, Division of Building Research, Ottawa K1A 0R6. Contract No. 033-1474/2694, March 1978.

DEY, B. GREGORY, A. F. and MOORE, H. 1979a. Monitoring and maping sea-ice breakup and freezeup of Arctic Canada from satellite imagery. Arctic and Alpine Research 11 (2): 229-242.

———, 1979b. Application of satellite images for monitoring snowline in the Yukon and N.W.T. Polar Record 19 (122): 473-483.

DEY, B., GREGORY, A. F. and MOORE, H. 1979c. Snow cover, snowmelt and runoff in the Mackenzie Basin. Proceedings of Canadian Hydrology Symposium on Cold Climate Hydrology, Vancouver, B.C., May 1979. Ottawa: N.R.C. Associate Committee of Hydrology. p. 450-460.

GILL, D. 1974. Significance of spring break-up to the bioclimate of the Mackenzie River delta. Reed, J. C. and Sater, John E. (eds.). The Coast and Shelf of the Beaufort Sea. In: Virginia: Arctic Institute of North America. p. 543-544.

HERLINVEAUX, R. H. 1975. Physical Oceanography of the Southern Beaufort Sea. Victoria, B.C.: Canada Department of Environment. Beaufort Sea Project Report No. 18.

IRWIN, R. L. 1977. Four meter antenna system for Landsat and NOAA reception. Canadian Journal of Remote Sensing 3 (1): 21-27.

KANE, D. L., CARLSON, R. F., and SEIFERT, R. D. 1975. Alaska Arctic coast ice and snow dynamics as viewed by the NOAA satellite. Proceedings of Third International Symposium on Ice Problems. Hanover, New Hampshire, August 1975. p. 567-577.

MACKAY, D. K. 1965. Break-up on the Mackenzie River and its delta, 1964. Geographical Bulletin 7: 117-128.

MARKO, J. R. 1975. Satellite observations of the Beaufort Sea ice cover. Victoria, B.C.: Canada Department of Environment. Beaufort Sea Project Report No. 34. 114p.

McCLAIN, E. P. 1974. Some new satellite measurements and their application to sea ice analysis in the Arctic and Antarctic. Proceedings of an Interdisciplinary Symposium on Advanced Concepts and Techniques in the Study of Snow and Ice Resources. Santeford, H. S. and Smith, J. L. (eds.). Washington, D.C.: National Academy of Science. p. 457-466.

RAMSEIER, R. O., CAMPBELL, W. J., WEEKS, W. F., ARSENEAULT, L. D. and WILSON, K. L. 1975. Ice dynamics in the Canadian Archipelago and adjacent basin as determined by ERTS-1 observations. Proceedings of International Symposium on Canada's Continental Margins and Offshore Petroleum Exploration, Texaco Exploration of Canada Limited, Calgary, Alberta, September 1974. Canadian Society of Petroleum Geologists. Mem. 4: 853-877.

REIMNITZ, E., RODERICK, C. A., and WOLF, S. C. 1974. Strudel scour: a unique arctic marine geological phenomena. Journal of Sedimentary Petrology 44 (2):409-420.

STRINGER, W. J. 1974. Morphology of the Beaufort Sea shorefast ice. In: Reed, John C. and Sater, J. S. (eds.). The Coast and Shelf of the Beaufort Sea. Virginia: Arctic Institute of North America. p. 165-172.

WADHAMS, P. 1976. Oil and ice in the Beaufort Sea. Polar Record 18 (114):237-250.

WIESNET, D. R. 1974. The Role of satellites in snow and ice measurements. Washington, D.C. NOAA Technical Mem. NESS, 58. 12p.