14th Congress of the International Society of Photogrammetry

Hamburg 1980

No. of commission: VII

No. of working group: W.G. VII,4

Type of paper: invited paper

Name and affiliation of author: Andrew Mather Cowan

Sea Ice Group,

Scott Polar Research Institute,

University of Cambridge.

Title: Sea ice morphology in the context of wave-ice interaction studies

Abstract:

The Sea Ice Group at the Scott Polar Research Institute in Cambridge has concentrated on wave-ice interaction studies over the past seven years. Field-work has been carried out in the Arctic Ocean, the Labrador Sea, the Bering Sea and the coastal zones of Greenland. SLAR, IRLS, laser and photographic sensors mounted on fixed-wing aircraft and helicopters and sonar on nuclear submarines have been used in experiments designed to establish such parameters as pressure-ridge spacing and the ratio of ridge sail height to keel draft. Information on wave decay in the Marginal Ice Zone has been linked to changes in such two-dimensional morphological parameters of the ice cover as floe-size distribution. Modes of analysis are briefly described.

It is some indication of the morphological and behavioural complexity of sea ice that there are over one hundred recognised terms describing its type, age, morphology and morphogenetic processes.

Given the average salinity of sea water at 35^{o}/oo, the freezing point is ≃-2^{o}C. The first crystals of ice to form are minute spheres of pure ice which develop into discoids to cover the water surface and freeze together. This initial stage, known as grease ice has a damping effect on capillary waves. In calm waters the layer thickens to become a transparent sheet of nilas (≤10 cm in thickness) which may bend elastically to a wave or, more usually, shatter. Finger-rafting is common where convergent stresses cause contiguous sheets of nilas to inter-digitate. In turbulant waters in which fragments 30 cm - 3 m in diameter form a close cover the pumping action and incessant collisions cause rims to form around fragment edges, this being known as pancake ice. With continued freezing of either nilas, pancake ice or merely a polycrystalline composite semi-continuous sheets of first-year ice will be formed (30 cm - 2 m in thickness). Such sheets are subjected to the environmental forces operating within and upon the ice canopy and fracture to form floes of varying size. The ice may survive a summer melt to become second-year ice which, due to continued growth and brine drainage, is thicker and less dense than first-year ice, thus having higher freeboard. Also, summer melting produces a regular pattern of numerous melt-water pools, a process appropriately called puddling. Should ice survive two melt seasons it becomes known as multi-year ice which is characterized by smoother hummocking than in younger ice and has, in general, a highly deformed 'mature' appearance. Puddling patterns are irregular and exhibit an interconnected well-developed drainage system. Multi-year floes may, eg. in the Beaufort Gyre, survive for 10 or more annual cycles, becoming extremely strong (being almost salt free) and very thick (up to 3 - 5 m), with high freeboard. Divergent stress fields, due in large part to wind action, cause fractures to open in the ice cover and, with young ice having formed in the open leads or cracks during periods of low temperature, convergent stresses force the edges together so as to form pressure ridges. The ridge network generally has a random orientation of its component ridges as it is composed of features of varying age. However, the pattern of leads and cracks is closely related to the most recent stress state and may be regular or unsystematic. Particular patterns or ridging and leads may be created when, for example, the boundary effect of a coast and its attendant fast ice is involved. Such patterns are often semi-parallel to the coast when multi-year Polar pack forces younger or fast ice against the boundary.

These and many other such links between process and morphology indicate the diagnostic value of form identification in remote sensing imagery analysis. The most satisfactory approach is to utilize the knowledge of one with experience in the field, both in the air and down on the ice. Sea ice morphology is so highly variable that the analyst must develop a feel for its shape, tonal variations, texture and environmental context. In visual analysis, or when using an interactive analytical system, judgements may then be made on the basis of knowledge of conditions prevailing at either the time of imaging or in analogous situations.

Much of the work of the Sea Ice Group has been directed at two problems. First, the nature of wave-ice interaction (Robin 1963a, 1963b; Wadhams, 1973a, 1973b) and, second, the statistical relationship between the surface and sub-surface topography of the ice canopy (Wadhams & Lowry, 1977; Wadhams, 1978a, 1979a, 1980). This discussion will be confined to the analysis of aerial imagery.

Wave measurements and under-ice morphometry were carried out in the Arctic Ocean (Swithinbank, 1972; Wadhams, 1972, 1973b) from two submarines in 1971 using upward-looking echo-sounders (Wadhams, 1973b, 1975) while airborne laser profilometry provided additional data on waves in ice. The results appertaining to wave attenuation indicated three modes of wave decay related to degrees of ice concentration (Wadhams, 1973b):-

(1) open icefield, ie. one composed of discrete floes of well scattered distribution. Here wave attenuation is achieved through a process of progressive reflection.

(2) Concentrated icefield, ie. being composed of small (20-100 m max. diam.) to medium (100-500 m max. diam.) sized floes. Here the basic mechanism of wave attenuation is similar; however, instead of discrete floes acting as individual reflectors, floe clusters act hydrodynamically as single large reflectors.

(3) Continuous ice cover. This may be sub-divided into:- (a) that resultant upon divergent stress conditions which cause a pattern of large (500 m + max. diam.) floes with separating leads, the latter rapidly freezing over in winter;(b) a ridge dominated continuous cover created under convergent stress conditions. Here the waves are ice-coupled and they may be attenuated in three ways:- creep, reflection from leads (edges) and reflections from keels and general ice-bottom protuberances.

The identification of such types of ice-field in remote sensing imagery analysis indicates therefore a particular wave energy attenuation regime. In early work the emphasis was placed on understanding the mechanisms of wave attenuation, but with only broad recognition being given to the reciprocal effect, ie. the genetic contribution to the spatial pattern and morphological components of any particular ice-field by wave action.

Of all the morphological parameters, that which emerges as being of greatest importance in the context of wave-ice interaction studies is floe-size distribution. As the waves propagate through an ice-field they are scattered and attenuated by the distribution of floe sizes they partially create.

It is in the Marginal Ice Zone that floe-size distributions are of particular interest, ie. the area of the pack relatively close to an open ocean margin and therefore subject to the influence of the wave climate of that ocean. The properties of the pack ice in such areas are markedly different from those of central Arctic ice; the Marginal Zone exhibiting extremely complex structural patterns in terms of variations in the morphological parameters of individual ice-floes and meso-scale ice formations. Such complexity results from a number of processes operating in the zone. Ice bends in response to incident waves and swell from the open ocean, and when the bending strain exceeds a critical magnitude fracture occurs. Variations in the physical parameters of the ice make the analysis of processes complex.

A new series of wave-ice interaction studies began in February 1978 with an air-sea operation in the Marginal Ice Zone off the coasts of northern Newfoundland and Labrador (Allan et al. 1979). This constituted the pilot study for two later experimental series in East Greenland waters. Floe bending, heave and surge responses to the incident wave field were measured while a wave buoy and airborne laser profilometer, SLAR, IRLS and aerial cameras provided data on wave decay and such morphological parameters as floe-size distribution. Wadhams (1973b) had proposed that wave-induced floe fracture would result in an outer zone of the pack, of variable width, composed of discrete floes whose mean diameter would increase with distance from the ice edge. The analysis of the Labrador Sea photographic imagery indicated a somewhat different morphogenetic process for the relationship between floe size and distance from the edge was not as predicted. Indeed the floe size data exhibits a distinct point of inflexion at which the exponential wave decay rate found in the outer 60 km of the pack becomes markedly higher (Figure 1). It would appear that the wave energy is no longer sufficient to cause the same degree of floe fragmentation.

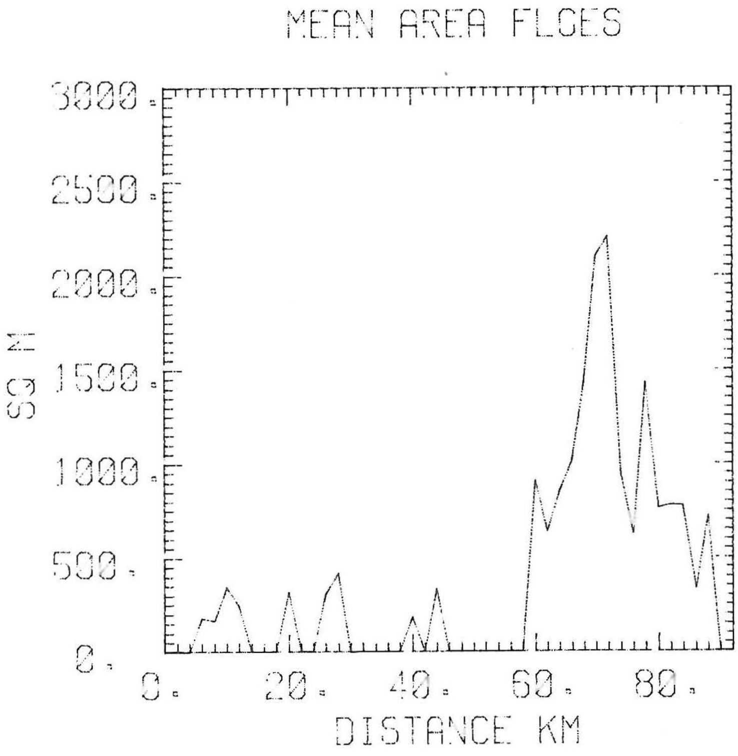
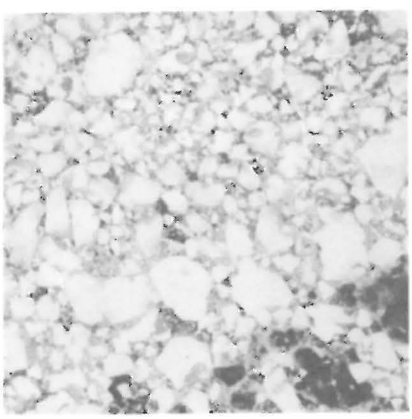


Figure 1.

The analysis, primarily of aerial photographs (Figure 2) was carried out with modular scanning image analyser. The basic system consists of a central processor, power supply, television scanner (vidicon) and a video monitor. The system is designed to make area and intercept measurements and count features within the image. Area measurements are made of features in the image conforming to pre-selected greytone levels; (Figure 3) this, in the case of imagery with good greytone contrast, enables one to analyse a series of related images with constant greytone selection levels. However, imagery of sea ice is rarely amenable to such convenient treatment and a subjective assessment of the ice feature/greytone match in each frame had to be made prior to area measurement. The accuracy of such a method is, of course, open to question, but there was no alternative to such an approach. Familiarity with the imagery undoubtedly led to a reasonable degree of accuracy, most especially after a number of trial runs made while assessing the imagery prior to analysis.

A flexidraw module was used to obtain individual floe/cake sizes (Figure 4). This is a joystick-controlled system for "drawing on" or "pointing to" features as seen on the video monitor. Here too a subjective element is introduced, for the accuracy of this method can vary between operators and with fatique. However, it is estimated by the author that an accuracy of better than ±5% is obtained with all but the smallest of features. Accuracy when drawing around small features is limited by the system itself for it operates by "Brightening up" in increments of individual picture elements, each having significant area.



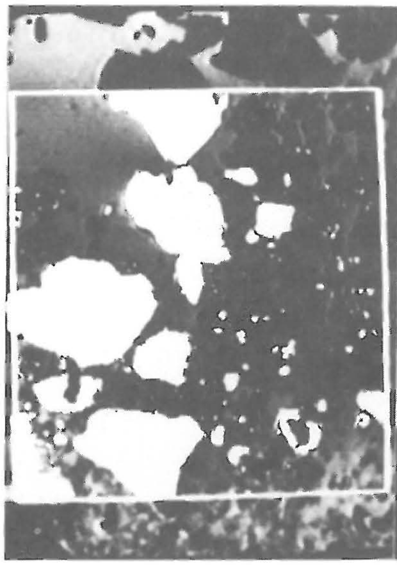


Figure 2
(70 mm film)

Figure 3

Figure 4

One of the system's features is a variable frame which is illuminated on the video monitor. A control on the central processor may be used to isolate the measurements being made to that area of an image shown within the variable frame. By matching this variable frame with an overlay sampling frame of known size superimposed upon the negatives an accurate measure of area and length of axes was maintained throughout the analysis. The sampling frame was slightly smaller than the negative frame size so as to avoid including poor quality imagery around the edges of the negatives, to minimize camera distortion of the image. During the course of the analysis, especially on changing frame to frame, the variable frame on the image analyser had to be adjusted slightly due to variations of image size on the video monitor, these being due to the optical system in the camera. Details of such changes were noted on the analysis sheet together with other system control details. Thus small changes in calibration could be taken into account when measurements were converted from picture elements, as shown on the central processor digital display, to real measurements.

The information extracted from each sampling frame was:

- area of open water;
- area of frame occupied by ice;

- area of frame occupied by floes and cakes;
- number of floes;
- number of ckaes.

In addition to the above information a systematic point sample was taken from each frame. A grid composed of 25 sampling points was located over the frame under analysis with a random element introduced by locating the central point in relation to coordinates selected by random numbers. This method proved the most efficient in providing maximum coverage while conforming to statistical sampling requirements. Where any one sampling point overlay a discrete floe or cake that feature's area was measured using the flexidraw. (Note: a cake = <20 m max. diam.)

All the area measurements of cover for each frame were converted into percentages of total sampling frame. Sampled ice feature measurements were converted into m^2. Thus detailed information on variations in cover, composition of cover and floe size distribution with distance from the ice edge was obtained.

However, the complex geometry and tonal differences exhibited by sea ice in an aerial photograph are such that much of the information is lost when using such an electro-optical system. Not only are greytone differences subtle and complex within each frame, but relative differences may vary in absolute tone along a transect. These difficulties are compounded when an attempt is made to use such a system to analyse Sideways Looking Airborne Radar imagery (Figure 5), arguably the most important active sensor for studying the two-dimensional morphology of sea ice. Its great advantage is that it can produce imagery with

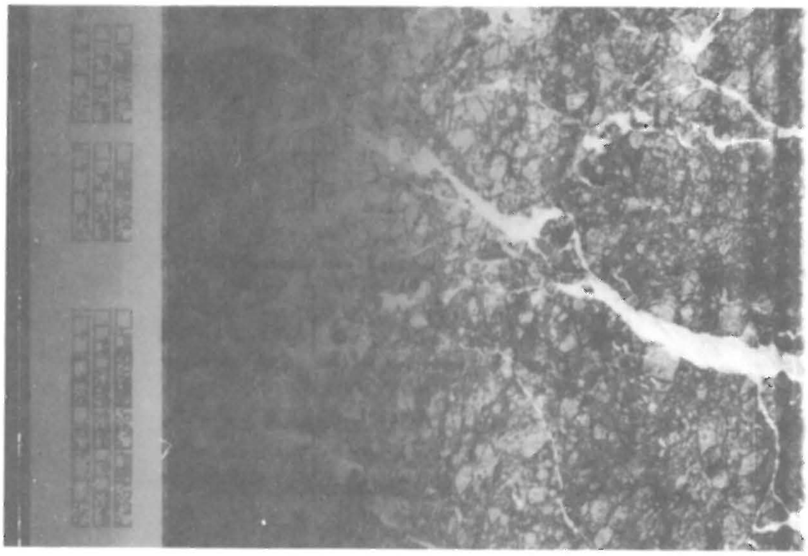


Figure 5

characteristic swath widths of 25-50 km in atmospheric conditions unsuitable for photographic imagery. It is possible to obtain the following information from such imagery:-

1. open or newly refrozen leads and polynyas can be differentiated from older ice.
2. A distinction between first and multi-year ice may in certain cases be made.

3. Thin ice can usually be distinguished from open water.

4. Pressure ridges and deformed ice can be delineated.

5. Floe size and shape can be discerned when the floes are geometrically well defined.

6. The junction of land and fast ice may be seen.

However, the problems involved in accurately interpreting such imagery in anything other than a semi-quantitative manner are very considerable. Of all the aforementioned points regarding interpretation it is that of clear geometric definition that poses the first problem. In close pack it is nigh on impossible to delineate discrete floes with certainty. Figure 5 shows imagery, obtained with an X-Band Motorola APS/94 D SLAR during a cooperative Arctic Ocean airborne/submarine operation, Exercise BRISK, in 1976 and has an image swath of 25 km range. Two of the main factors critical to the interpretation of this particular imagery are the across-range deterioration in azimuth resolution and variations in the alignment and spacing of scan lines. The tonal inconsistencies and resolution problems largely restrict an analysis to textural interpretation. Leads show very clearly as light areas, but level ice shows as light areas which may closely approximate the tone exhibited where leads are present. Ridging and rough surface topography show as various darker tones, but experiments involving ground truthing show that the relationship between tonal differences in the SLAR image and the ice surface is a complex one. Recent work, especially at the Canadian Centre for Remote Sensing, on Synthetic Aperture Radar shows promise both as an improved operating system and as regards interpretation.

The Thermal Infra-Red Linescan imagery (Figure 6), also imaged during the BRISK exercise, was obtained using a Singer Reconofax 13 line scanner. The scanner looks to 60° port and starboard, and from an altitude of 4000' produces a 4.2 km wide image swath. The main problem in using such imagery for morphological measurements is again geometric. The size of

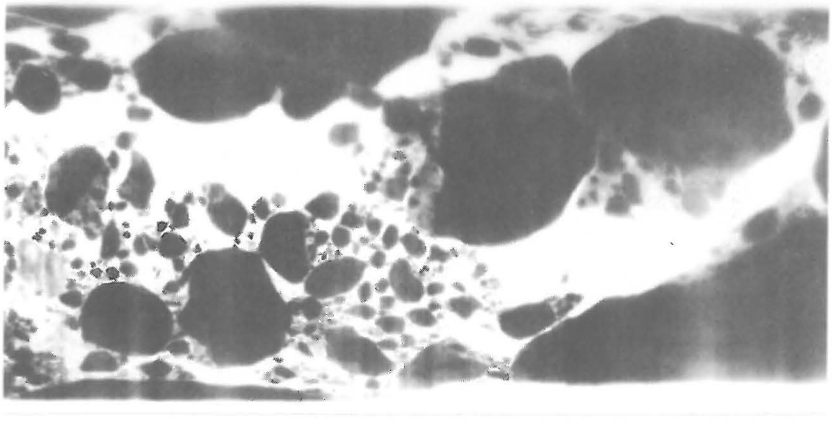


Figure 6

an area recorded by the scanner is a function of the scan angle. Consequently, the recorded image is distorted in the y-direction because of a uniform scan rate. In the x-direction a small strip of double coverage will occur, which is the theoretical limit of resolution. No x-error will occur at the centre of the display if the adjacent scans are fitted together without gaps or overlaps, ie. if the differential changes of aircraft tilt are negligible from scan to scan and if the film speed corresponds to the ground speed. In the y-direction, however, a large-scale error occurs. This being the case, measurements of floe-size, etc. are best made along a narrow central band of the image.

Work on wave-ice interaction subsequent to that in the Labrador Sea was carried out in Kong Oscars Fjord in East Greenland in August-September 1978 and 1979 and involved more complex instrumentation and methodology in a Marginal Ice Zone fjord situation (Wadhams, 1979b; Wadhams and Squire, 1980). The analysis of the remote sensing imagery obtained during these experiments has the following objectives:-

(1) to establish along transect change in the two-dimensional morphological parameters of discrete floes, ie. floe-size, leading edge to the incident wave train, shape and orientation; all these being measured for both floe surface and sub-surface areas, which may differ significantly.

(2) To examine the dispersive/clustering behaviour of the floes.

(3) To attempt to discern the disruptive effect of the observed fjord surface water circulation on the morphological distributions measured along the transects, ie. to detect near-shore deviations from the regional trend up the fjord.

(4) To seek to elucidate the relationship between, eg, floe-size distribution and wave attenuation. That is, to extend the work carried out in the Labrador Sea and establish, if possible, characteristic relationships between given incident wave fields and wave attenuation and ice morphogenesis.

On the basis of the negative experience with the electro-optical analyser a new approach has been taken to image analysis. The choice of a system was dictated by a desire for simplicity and a maximised interactive aspect. This so that all forms of imagery could be tackled with the optimum use of the operator's interpretative expertise. A modular coordinate digitizer and digital planimeter system is now being used successfully. Simultaneous detection of a range of fundamental spatial parameters including area, perimeter, maximum diameter, form factor, centre of gravity, etc. has greatly simplified the first stage of morphometric analysis. The interactive element being virtually absolute as all that is required is for the operator to trace the perimeter of a feature with a cursor; the evaluation tablet upon which the image is placed or projected having a resolution of 0.1 mm.

Observations made during remote sensing flights in the Labrador Sea of the overall patterns exhibited by the ice provide a context in which to view the detailed measurements discussed above. Two main complicating pattern types are apparent:- a distinct repetitive banding of ice and open water, (Figure 7), and the presence of eddy-like patterns in the ice at different scales (Figure 8).

The banding varies in character, but all forms have a significant effect on measurements made along a sampling transect. Owing to the action of winds and currents which act as both transport and sorting mechanisms a complex pattern composed of ice fragments with different 'histories' may be created. When an imaging transect is carried out with the object of measuring, for example, floe sizes in relation to wave energy measurements

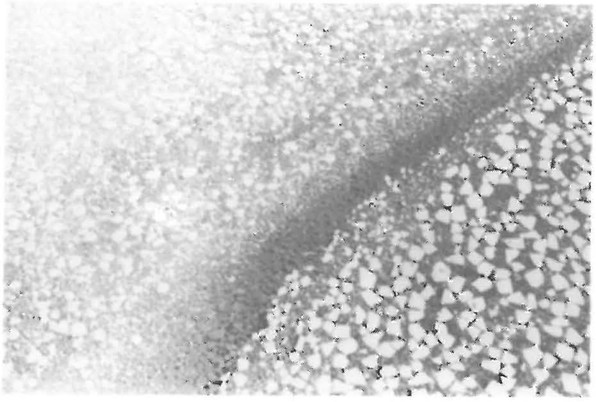


Figure 7
(Scale 1:27,500)

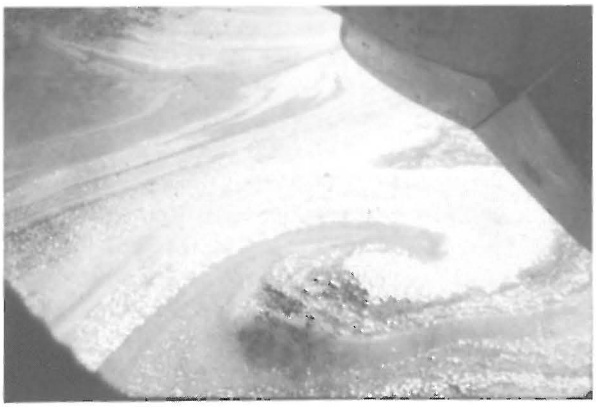


Figure 8
(Scale 1:27,500

such mixed patterns may provide misleading data.

The complicating effect of banding is exacerbated when sections of ice cover so patterned are formed into eddy-like shapes. One transect may cut across such a feature, which exist at scales varying from as low as 100 m to many kilometres in diameter, so as to pick up in the sampling repetitive variations in size measurements. The possible existence of mesoscale eddies along the outer edge of the Labrador Current has been noted by Allen and Huntley (1977). More importantly Alekseev et al (1972) discuss the increasing complexity of the circulation field of the Labrador Current when the current approaches the northern slope of the Hamilton Bank. It is in this area that eddies become more common as opposed to further north where the Current has, for example, fewer eddies than the West Greenland Current. The 200 m isobath appears to be influential in the creation of small local eddies to the right of the S.W. water transport above the continental slope of the Atlantic Shelf. Eddy-shaped ice patterns therefore, apart from being complicating factors in sampling techniques, may serve as indicators of oceanographic eddies.

A new programme to study the ice edge of the East Greenland Current follows logically from this background and it can only be carried out thoroughly within the context of an all-encompassing study of the character, morphology and composition of the entire ice canopy of the Current. All the aforementioned parameters and characteristics of an ice canopy must be considered together with the action of wave, wind and current on the pack. It is our intention to utilize all available remote sensing imagery of the Current, the core of which will be a complete year's coverage of satellite imagery, ie. LANDSAT, TIROS, etc. (Figure 9). An attempt will be made to characterize ice canopy composition zones defined in terms of concentration, ice type composition, (thus giving approximate age, thickness and the contribution of locally generated ice to the cover), roughness and ridging coefficients, overall extent and variations in that extent, and proximity to differing ice canopy composition zones. (This aspect of the programme may be related back to the wave attenuation findings discussed earlier). Floe-size distributions, and those of other morphological parameters, will be measured latitudinally and longitudinally. Preferred orientations of leads and the maximum diameters of polynyi will be monitored together with fluctuations in extent and number. It is known, for example, that certain large polyni are to be found permanently or semi-permanently at particular locations along the coast. Zones of marked

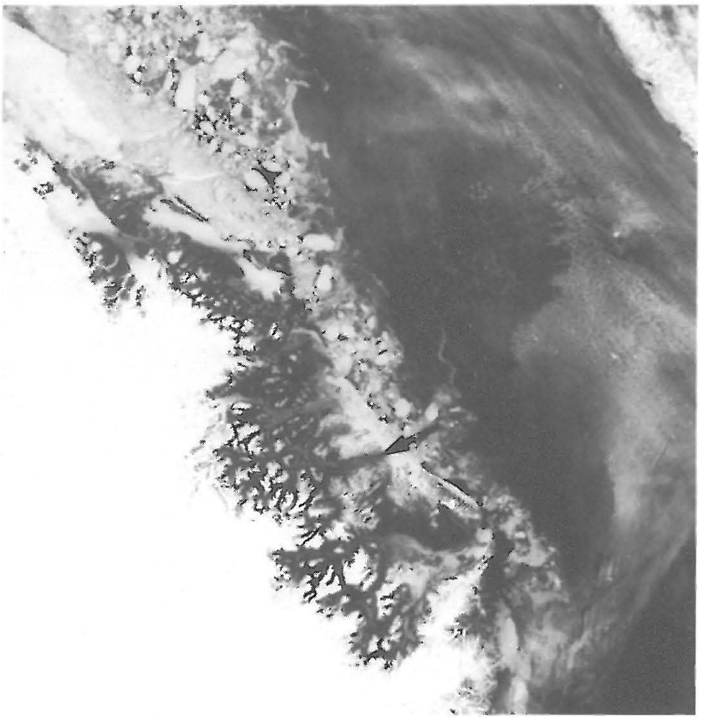


Figure 9
Tiros image (VIS) (Note: arrow indicates Kong Oscars Fjord, 72°15'N 23°W)

fracture will be delineated and points of fracture genesis located. Banding patterns will be viewed in terms of dimension, component floe-size variations and the relationship of such patterns to ice eddies. For example, the possibility of the 'layering-on' of bands of varying floe-size composition to the ice-edge by eddies will be examined. The structure, dimensions, wavelength and period of ice edge eddies together with their spatial and temporal variations or stationarity should lead to an understanding of the main aspects of their behaviour:-

(1) how far within the pack may an eddy's influence be detected? In other words, from what 'skin-depth' from the ice-edge do these mechanisms advect floes to be components of the eddy?

(2) What quantitative effects does such a process of advection and gyration have upon the composition of the ice canopy?

(3) What proportion of the ice cover and what absolute quantity of ice is advected out into, for example, the otherwise open Greenland Sea beyond what may be defined as the 'normal' ice edge for any particular time of year?

The fundamental scientific purpose of such research programmes is to provide information of value to the understanding of ice dynamics and the influence of the ice cover on, for example, climate and marine biological productivity. However, more immediate applications are envisaged. The definition of a set of parameters indicating morphogenetic and oceanographic processes, together with the development of near real-time imagery and data analysis, will be of value in ice-reconnaissance and meteorological forecasting and analysis.

REFERENCES

ALEKSEEV, A.P., B.P. Kudio, V.N. Yakovlev, A.F. Fedoseyev and A.A. Barinov (1972). Some aspects of water circulation in the Northwest Atlantic in 1960-69. Spec. Publn. 8, 149-165, Int. Comm. for NW Atlantic Fisheries, Dartmouth, N.S.

ALLAN, A.J., P. Wadhams and A.M. Cowan (1979). An experimental study of wave-ice interaction and floe flexure in the pack ice of the Labrador Current. Centre for Cold Oceans Resources Engng., Memorial Univ., St. John's Tech. Rept., in press.

ALLEN, A.A. and D.A. Huntley (1977). Currents at the offshore edge of the Labrador Current. Proc. 4th Intl. Conf. on Port & Ocean Engng under Arctic Conditions, St. John's, Nfld., 2, 927-937.

ROBIN, G. de Q. (1963a). Ocean waves and pack ice. Polar Record, Vol. 11, No. 73, p 389-93.

ROBIN, G. de Q. (1963b). Wave propagation through fields of pack ice. Phil. Trans. Roy. Soc. A, 255 (1057), p 313-39.

SWITHINBANK, C. (1972). Arctic pack ice from below, in: Sea Ice Conference Proceedings (Karlsson, T. ed.), Reykjavik, pp 246-254.

WADHAMS, P. (1972). Measurement of wave attenuation in pack ice by inverted echo sounding. In Sea Ice (T. Karlsson, ed.), Natl. Res. Counc. of Iceland, Reykjavik, 255-260.

WADHAMS, P. (1973a). Attenuation of swell by sea ice. J. Geophys. Res., 78(18),3552-3563.

WADHAMS, P. (1973b). The effect of a sea ice cover on ocean surface waves. Ph.D. thesis, Univ. Cambridge. 223 pp.

WADHAMS, P. (1975). Airborne laser profiling of swell in an open ice field. J. Geophys. Res., 80, 4520-4528.

WADHAMS, P. & R.T. Lowry (1977). A Joint Topside-Bottomside Remote Sensing Experiment on Arctic Sea Ice. In Proceedings of the 4th Canadian Symposium on Remote Sensing, 407-423.

WADHAMS, P. (1978). Characteristics of deep pressure ridges in the Arctic Ocean. Proc. 4th Intl. Conf. Port & Ocean Engng. Under Arctic Condns., (D.B. Muggeridge, ed.), Memorial Univ., St. John's, 1, 544-555.

WADHAMS, P. (1979a). A comparison of sonar and laser profiles along corresponding tracks in the Arctic Ocean. In Sea Ice Processes and Models (R. S. Pritchard, ed.), Univ. Washington Press, Seattle, 283-299.

WADHAMS, P. (1979b). Field experiments on wave-ice interaction in the Labrador and East Greenland Currents, 1978. Polar Record, 19(121), 373-376.

WADHAMS, P. (1980). A further analysis of sonar and laser profiles from corresponding tracks in the Arctic Ocean. To be submitted to J. Glaciol.

WADHAMS, P. & V.A. Squire (1980). Field experiments on wave-ice interaction in the Bering Sea and Greenland waters, 1979. Polar Record, in press.