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Glaciological and Marine Biological Studies at
Perimeter of Dronning Maud Land, Antarctica
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INTRODUCTION

The overall objective of this investigation was to utilize Landsat imagery to analyze changes in the Dronning Maud Land coastline and to obtain statistical data on ocean dynamics, plankton distribution, and sea ice and iceberg distribution in this region of the Antarctic. The specific objectives were as follows:

1. To develop a technique for assessing the rate of iceberg calving from the Dronning Maud Land coast so that the mass balance of Antarctica in general and of the Dronning Maud Land Ice Dome in particular can be understood.

2. To study iceberg drift in the coastal waters of Dronning Maud Land and to develop techniques for charting marine currents in this area.

3. To determine the distribution and frequency of large sheets of plankton in these coastal waters in order to better understand their relationship to the primary and secondary production rates, and the geographic distribution, of organisms higher in the food chain.

4. To study the statistical distribution of sea ice and icebergs in this area in order to determine any prevailing patterns which might affect the selection of a site for a new scientific station on the Dronning Maud Land coast.

The first imagery for this investigation was received in August 1975, and over the following year altogether 67 imageries of the test area were received, from the following periods:

February 1975	5
October 1975	15
November 1975	15
December 1975	14
January 1976	5
February 1976	13

This number of imageries were significantly less than anticipated and planned for. And it will be shown below

that for most objectives of this investigation the imageries have been too few, and too unsystematically collected, to allow quantitative conclusions. But at the same time the potential of many of the methods have been verified.

TECHNIQUES

MSS 7 of all the negatives received have been copied in BW at 1:1 mill scale. The other bands have also been used for selected imageries to attempt differentiation between ice floes and icebergs, and to identify areas of plankton concentrations, with inconclusive results.

The drift determinations of icebergs and floes have been done by tracing these on BW MSS 7 taken on successive days. Correct positioning has been assured by having parts of the ice shelf included in the imageries.

The frequency distribution of the size of the floes has been determined from BW (1:500,000 scale) by a semi-automatic planimeter.

Some of the imageries have been investigated in an additive colour viewer to attempt delineation of areas of plankton concentrations. This investigation was negative.

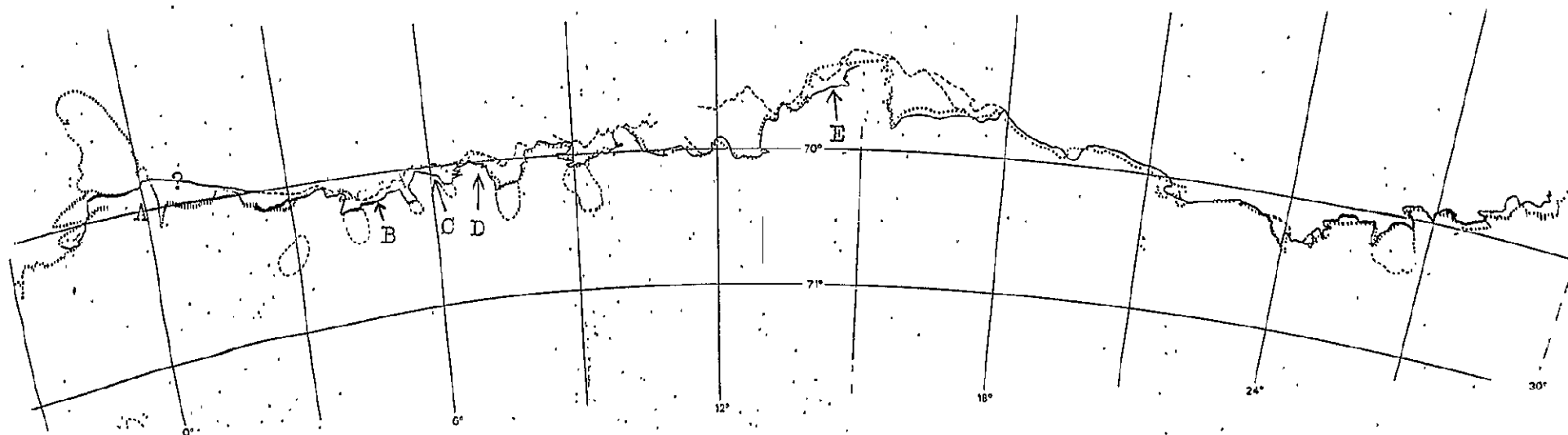
The best method to distinguish between the ice shelf edge and the fast ice, and to bring out ice rises on the ice shelf, has been to copy the MSS 7 negatives at 5 - 10 times "normal" exposure.

RESULTS

Assessing rate of iceberg calving to evaluate mass balances

Figs. 1 and 2 show the Dronning Maud Land coastline from 10°W to 29°E, as determined from Landsat imagery, and a comparison with former mapping. The map has been made at scale of 1:1 mill, and the Landsat imageries have been positioned by use of rock outcrops of known positions, which in some cases have involved making a strip, of imageries taken sequentially, to make the tie from outcrops

DRONNING MAUD LAND, ANTARCTICA



Solid line = Coast line determined from Landsat imagery

Dotted line = Coast line determined from Horsk Polarinstitut's 1951/52 and 58/59 air photography

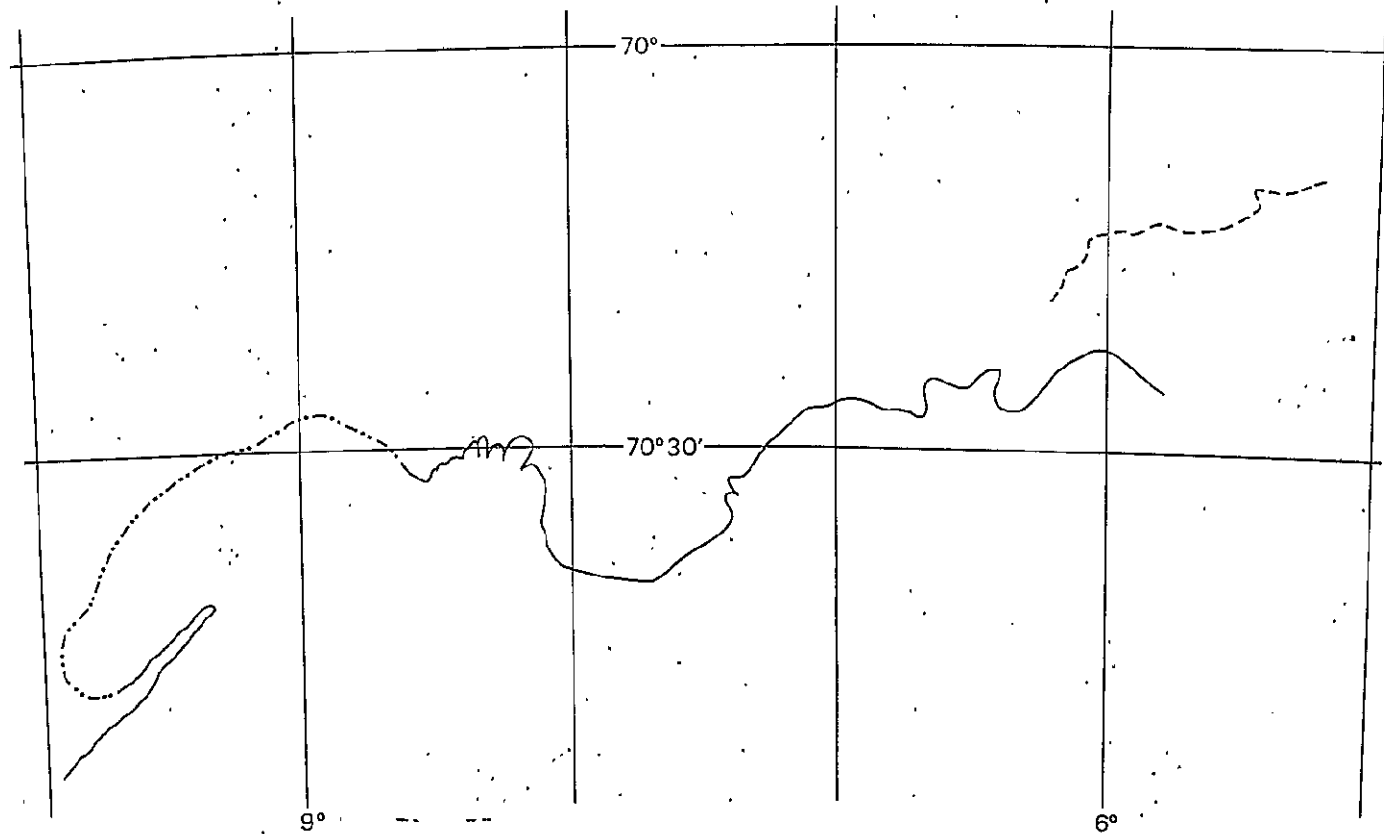
Heavy dashed line = Outer limit fast ice at time of photography/imagery.

Thin dashed line = Outline of ice rises

Scale:

0 100 200 km

DRONNING MAUD LAND, ANTARCTICA



Solid line = Coast line determined from Landsat imagery
Dashed line = Outer limit fast ice at time of photography/imagery
Dotted-dashed line = Coastline uncertain

0 25 50 km

1:1,000,000

to the coast. The former mapping is based on airphotography mostly from 1951/52 and 1958/59 with limited ground control, and exists mostly as unpublished maps here at Norsk Polarinstitutt. Some of the differences in coastline shown in Figs. 1 and 2 may be due to errors in the earlier mapping, or in positioning of the Landsat imagery. Examples of this may be the coastline from 16 to 21°E in Fig. 1, the impression is that the two coastline determinations show the same shape, and that stretching/compressing the older mapping in the east/west direction would bring the two determinations into close accord. That errors are present in the east/west determinations of the earlier aerial photography is very likely.

The major changes between the earlier photography and the Landsat imagery must be real, however. In Fig. 1 are shown five areas where the differences in coastline determinations most likely are caused by calving of large parts of the ice shelf. Area A, Trolltunga, broke off around 1967 as was described in our proposal for this investigation. We believe that the calving of areas B, C, D, and E have not been described before. Close inspection of Fig. 1 will also reveal many smaller areas of differing coastline, which have a form indicating that these differences too are caused by calving. However, we are hesitant to evaluate these because of the obvious uncertainties in the positionings. Areas A - E cover a total of 6,275 km², which assuming an average thickness of 200 m equals 1,255 km³. This corresponds to an average minimum calving rate from this part of the Antarctic coastline of around 60 km³/year. This clearly is a very minimum determination, as only a few large areas are included, and as no account is taken of the changes in coastline caused by the outward movement of the ice shelf. The calving of the ice shelf takes place at intermittent and possibly irregular intervals, and determinations over many more decades are probably needed for accurate assessment of the average calving rate. On the assumption of steady state the average calving rate should equal the rate of mass outflow. It is interesting to note that the mass outflow computed from this same sector by Budd, Jenssen and

Radok (1971, p. 41) is about $100 \text{ km}^3/\text{year}$. Considering the errors of our minimum estimate, as well as the errors clearly present in their estimate, these two estimates are in good agreement.

The comparison between the earlier map of the coast and that made from the Landsat imagery is especially hampered by the lack of ground control in the early air photography. It was hoped during this investigation to make more precise comparisons, by making several maps from repetitive Landsat imagery, and thus determine outflow rates and areas of large calvings. We believe that this still is a feasible project, and that the applicability of the technique is demonstrated by the above results. Unfortunately, however, we have not received any imagery which has permitted us to carry out this part of the project. We have received only a few instances of repetitive coverage of the same area at time intervals greater than one month, and none greater than three months. These have been examined for any changes in the coastline, but no changes have been detected. The fastest ice shelves have an outward movement of around $500 \text{ m}/\text{year}$, so with the few examples we have it would have been very fortuitous should we have been able to detect changes over such short intervals. What we needed were imagery covering an interval of minimum one year, preferably with intermediate imagery as well.

Despite the lack of such imagery, we believe the results of this part of the investigation to be significant and useful. We have been able to produce a coastline map, which will now serve as reference to compare with future mapping. This is an important result, even though the map contains some defects. As will be apparent from Figs. 1 and 2, there are some gaps, notably from 6°W to 2°W , and at 15°E . We would also have liked better control on the positions, as we know that there can be errors in the Landsat positions (Nye and Thomas, 1974). We were able to make a small test of the latter during the 1976/77 Norwegian Antarctic Research Expedition, which positioned the coastline from about 44°W to $9^\circ 30' \text{W}$, with an estimated

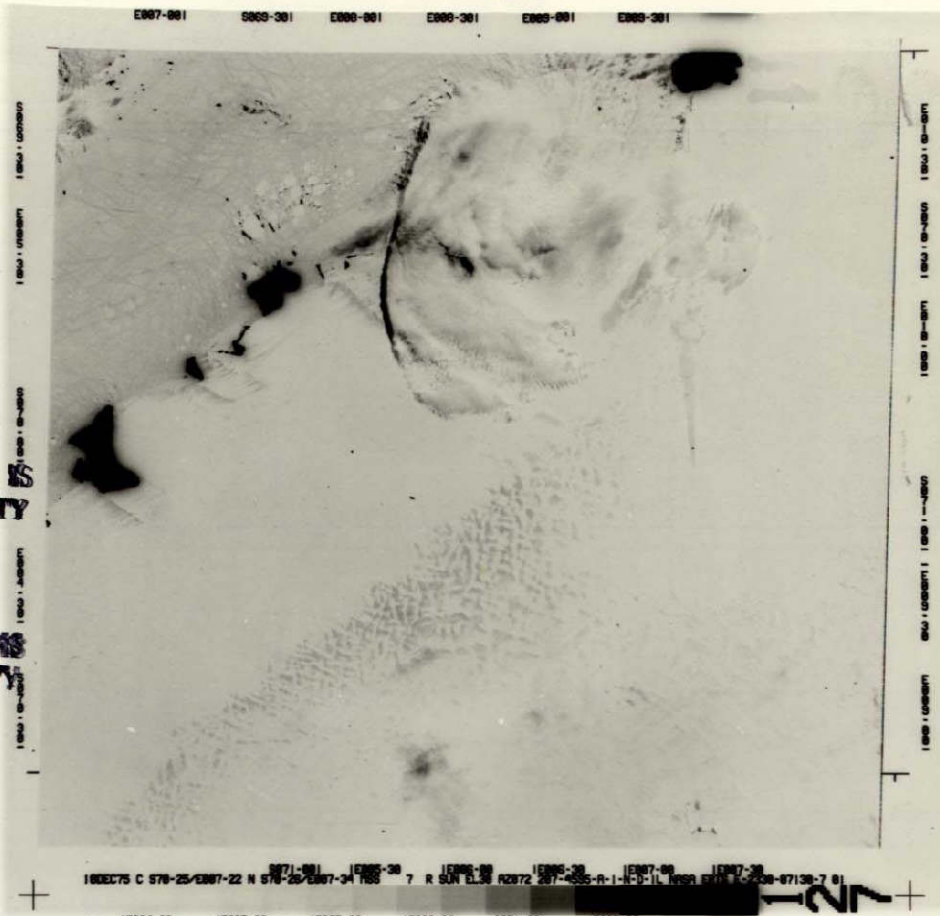
precision of ± 200 m. We were able to compare this with the coastline on imagery 2034-08125, which extended to 10°W , and the errors in the image were found to be less than 500 m. However, a thin cloud bank obscured the coast on the imagery to such an extent that it is not possible to delineate the coast with absolute confidence (Fig. 2), and for this reason we cannot closer estimate the positioning precision of this image. During the planned 1978/79 Norwegian Antarctic Research Expedition we intend to make position determinations of the whole coast covered by Fig. 1. This control will allow us to make a better assessment of the reliability of the Landsat-determined coastline.

Drift of icebergs and ice floes

Fig. 3 shows imageries at successive dates (18 and 19 December 1975), from which drift speed determinations were made of the cluster of (probably) icebergs and floes around $6^{\circ} - 7^{\circ}\text{E}$. The ice moved westward at between 12 and 20 km/day, with most determinations in the lower range. The only other instance of Landsat imagery sufficiently close in time and space to allow drift determinations covered a three day period from 27 to 30 October 1975, when velocities varied between 9 and 13 km/day, with an average of 10 km/day. This took place at $3^{\circ} - 5^{\circ}\text{E}$, the ice was moving westwards and there was a divergence in the field amounting to $1.0 \times 10^{-5}/\text{sec}$. These velocities are close to the determinations by Tchernia (1974) and Swithinbank, McClain and Little (1977), and the feasibility of the method is clearly demonstrated. But the data set is too small to make any conclusions about the marine currents in the area.

A particular problem that we have not resolved satisfactorily is to distinguish between ice floes and icebergs. We expected to be able to distinguish between these at low sun angles by the shadow of the icebergs, which are approximately 20 m above sea level. However, when floes and bergs are together there is commonly open water on one side of icebergs, because of differential

Fig.3



movements, making it often impossible to distinguish the shadow of the berg. On the other hand it cannot be assumed that open water within an ice mass indicates presence of icebergs.

A second method by which we had hoped to distinguish between floes and bergs was to use imageries at different MSS bands. We expected that the sea ice, which at times is wet with sea water, should be distinguishable from the icebergs. Because the imageries of floes/bergs available have been mostly from early in the season (October to December), when both the sea ice and the bergs are covered by snow, it has not been possible to verify this satisfactorily. This question can probably not be solved without some ground truth. For example, we consider it likely that Fig. 3 shows some icebergs surrounded by sea ice, but without ground truth we cannot prove this. The shapes are of course also important, if the shape is rectangular then the chances increase that the object is an iceberg.

A combination of several remote sensing techniques would probably resolve these questions, and there is no doubt that repetitive imagery of an area with recognized floes and bergs would be a cheap and very useful technique for charting the marine currents. Because the floes are essentially surface wind/current driven, while the bergs show the combined effect of the surface winds and the integrated ocean currents down to 2-300 m, the tracking of both together would give much oceanographic and meteorological information.

Distribution and frequency of large sheets of plankton

This aspect of the investigation was inconclusive. We did not detect any sheets of plankton, despite various attempts at technical enhancement to bring out the expected brown-red coloured sheets. One reason for the failure was that we received very little imagery that was suited for this part of the investigation. From biological considerations it was clear that the best possibility of detecting the plankton was on mid-late summer imagery.

with large areas of open water. Of the 67 scenes received, only four taken in December or later in the summer contained large significant areas of open water. In view of the results of the 1976/77 Norwegian Antarctic Research Expedition this number was clearly so small that it would be very unlikely that plankton sheets should be included in the imageries. On that expedition an echosounder was run over 10,000 km track line during January and February 1977, with only small registrations of zooplankton, and only at one occasion were plankton swarms seen at the surface. The larger amounts of zooplankton were observed 2,000 kms north of Antarctica, and only small catches were made near Dronning Maud Land. Thus we believe that the zooplankton possibly is not as plentiful near the continent as has been suggested by some. The imageries we had available to test this question were clearly insufficient.

Distribution of sea ice and icebergs

Table 1 shows the frequency distribution of the size of the floes, as determined from BW (1:500,000) by a semi-automatic planimeter. Six cases during October and November 1975, covering altogether an area of over 72,000 km², have been considered (Table 1). Because of high cloudiness it was not possible to find suitable imageries for the rest of the investigation period. Only floes with an area greater than 10 km² have been considered, as the determination of the area of smaller floes becomes unreliable.

Around Svalbard in the Arctic there is an indication of a bimodal distribution in the floe sizes (Vinje: Landsat Investigation No 28 540. Final Report). This is not established in the more limited material from Antarctica. Instead there is a more or less irregular decrease of the percentage coverage from about 6% towards 1-2% as the sizes of the floes increase from 10 to 100 km². The mean area of the 636 floes considered is 30 km².

Table 2 shows the percentage covered, with respect to the total amount of ice, of the different floe sizes.

TABLE 1

C O V E R A G E

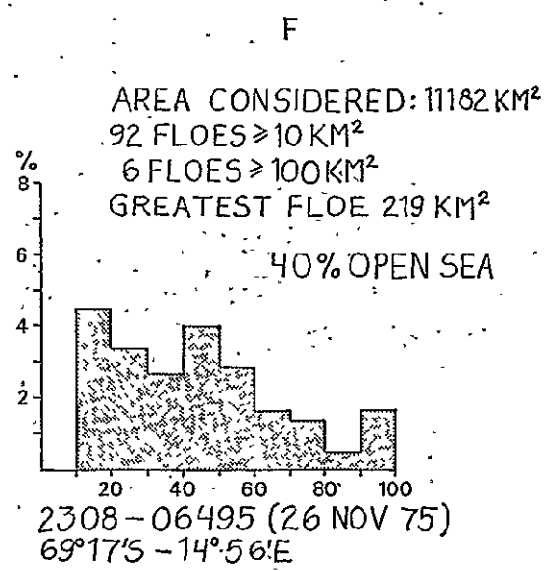
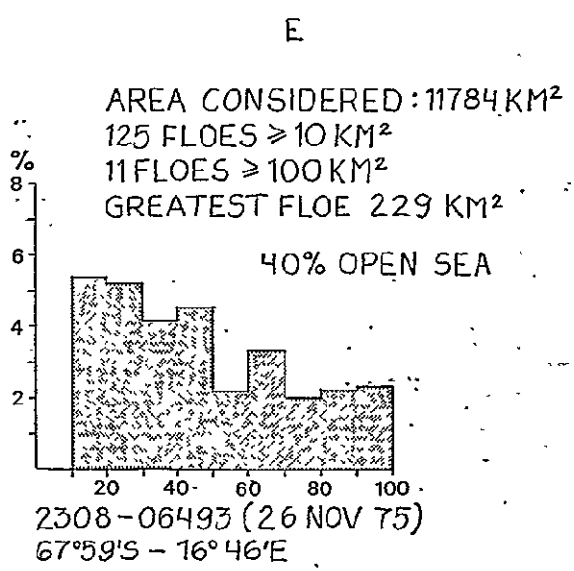
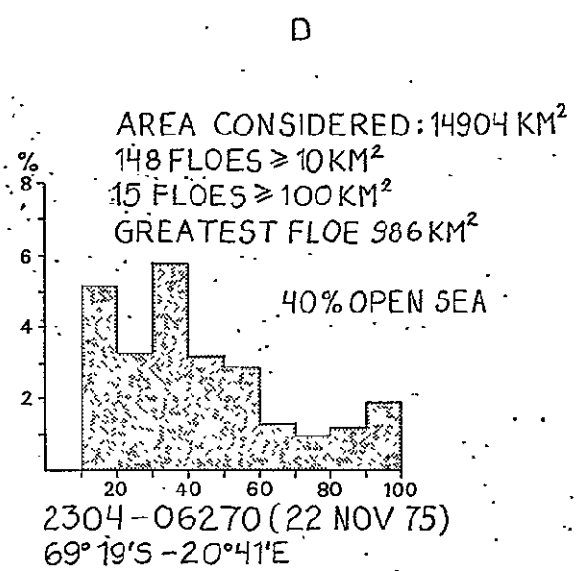
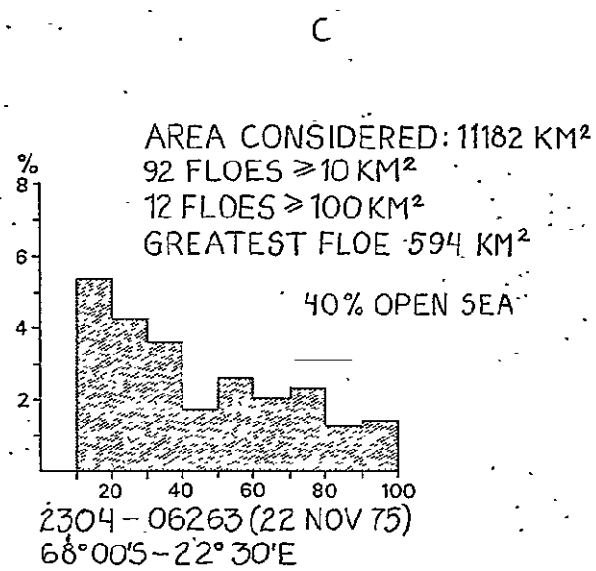
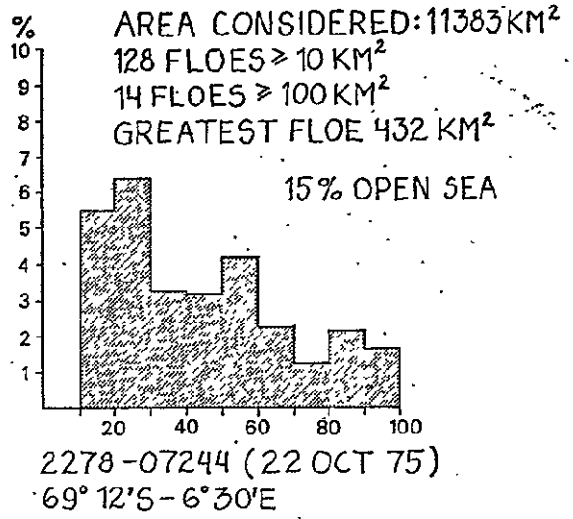
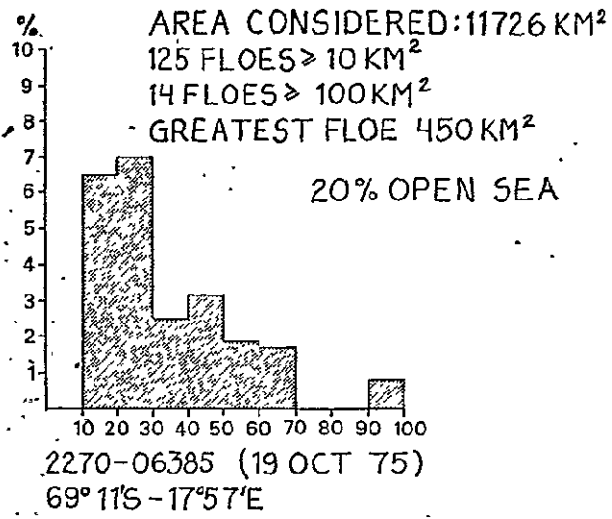


Table 2

Percentage contribution to the total ice covered area of floes of various sizes

Imagery	Ice covered area, km ²	Floe-size intervals, km ²		
		0-10	10-100	above 100
A	9380	37	29	34
B	9680	34	35	31
C	6710	26	49	25
D	8940	23	44	33
E	7070	22	47	31
F	6710	48	38	14
Mean	8080	32	40	28

The table shows mostly only small differences in the percentage coverage from class to class. This indicates that the number of floes roughly changes with a factor of 10 from class to class, i.e. an exponential relationship between number and area of floes.

It was intended to evaluate the sea ice distribution to determine any prevailing patterns that might affect the selection of a station site. As should be clear from the previous remarks, there were too few suitable imageries available to make any approach at this problem. We needed repetitive imagery of the coast from January and February to recognize those possible areas where the fast ice and ice floes might hinder access.

Other results

One important result of the investigation has been the recognition of several ice rises, that could be important sites for future ice drillings for paleoclimatic studies. These ice rises are shown on the map, Fig. 1, and in Fig. 4, and as discussed in the 3rd Quarterly Report of this investigation, they have been most easily discovered by making overexposed copies of the MSS 7 imagery. Table 3 gives the dimensions of the ice rises,



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Part of Landsat imagery 2278-07250, MSS 7, showing four ice rises at the Dronning Maud Land coast between 3 and 7°E. These ice rises are only slightly above the general surface of the ice shelf, and can be very difficult to see from ground level. They may have occupied fairly constant positions over long time periods, and promise to be important sites for paleoclimatic studies.

as measured from BW 1:1 mill imageries

Table 3

Ice rise position	Length,km	Width,km	Length/width
1) 71°25'S, 1°00'W	31	17	0.55
2) 70°30'S, 3°00'E	32	19	0.59
3) 70°20'S, 4°30'E	29	19	0.66
4) 70°20'S, 5°30'E	13	10	0.77
5) 70°10'S, 6°30'E	12	9	0.75
6) 70°20'S, 7°30'E	31	19	0.61
7) 70°20'S, 9°00'E	42	24	0.57
8) 70°10'S, 26°00'E	41	34	0.83

The Landsat imageries have also provided much other information on land phenomena. The major ice streams are shown with their flowlines, and blue ice field and snow drift patterns are clearly brought out. One interesting and unexpected discovery was the significant melt phenomena shown in Fig. 5 a) and b), from 10 January and 14 February, 1976. We see here a blue ice field, which, presumably because of lower albedo, experiences significant melting, with the melt phenomena extending many kms downslope. Some of the darker areas could at first glance be mistaken for solid rock, but examinations of all MSS bands show that the phenomena become very indistinct in bands 4 and 5, and it is clear that the imagery shows only water, snow and ice. Note also the persistence of the snow drift patterns south of the melt phenomena.

SIGNIFICANT RESULTS

As the area of this investigation is remote and not easily accessible, it is clear that the Landsat imageries will give original information of great interest. The most important result in our view is the production of a nearly complete map of the Dronning Land coastline from 10°W to 29°E. Based on this we have determined that for the past 20 years the minimum calving rate from this part of the coastline has been 60 km³/year. The coastline map



Fig. 5 a) Part of Landsat imagery 2353-05581, MSS7, taken on 10 January 1976, at scale 1:1 mill, with centre of picture at $70^{\circ}45'S$, $27^{\circ}E$, oriented with N, and downslope, upwards parallel the short sides.



Fig. 5 b) Part of Landsat imagery 2388-05515, MSS7, taken on 14 February 1976, with scale and orientation as for Fig. 5 a), and covering approximately the same area. Note the various melt phenomena extending downslope from blue ice fields, and the unchanging pattern of the snowdrifts south of the melt features.

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will also serve as an important data set to compare with future studies.

We have measured the drift speeds of ice floes and bergs to between 9 and 20 km/day, and we have found that the number of ice floes of given size decreases exponentially with size, so that each size class covers approximately the same area.

We have identified and measured a series of ice rises, which could be important localities for future paleoclimatic studies. We have also discovered large melt phenomena at blue ice fields around $70^{\circ}45'S$ and $26-29^{\circ}E$.

CONCLUSIONS

We received only about 1/4 of the imageries planned for this investigation, and the resulting lack of repetitive imageries has prevented us from reaching satisfactory conclusions about most of the problems this investigation was aimed at. On the other hand, the number was adequate to prove the potential of most of the planned investigation. The Landsat imageries have clearly a remarkable potential for investigation of many problems in inaccessible areas, with which costly expeditions cannot hope to compete. For us working in polar areas the Landsat imageries already available will constitute an important data source, and we hope that future developments will be such that we can continue to receive imageries of Antarctica.

ACKNOWLEDGMENTS

This report has been prepared in cooperation with Mr. T. Vinje at the Norwegian Polar Research Institute. Mr. Ø. Finnekåsa, also at this institute, prepared the photoproducts and extracted the necessary back ground data for the investigation.

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