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ICE DISPLACEMENT VECTORS MEASURED IN NORTON SOUND AND THE ADJACENT BERING SEA 1973 - 1979

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ABSTRACT

Twenty maps showing displacements of identifiable ice floes within Norton Sound and the adjacent Bering Sea are presented. These maps document ice motion during thirty-one 24-hour periods and six 18-day periods between 1973 and 1979. On several occasions individual floes could be tracked for two successive observation periods, making 48-hour and 36-day observation periods.

Three general modes of ice behavior within Norton Sound were observed: (in order of occurrence) outbound ice, inbound ice and gyre. Not only was the outbound ice mode observed most frequently, but the velocities during those periods appeared to be higher than during the inbound mode. Hence, the general trend is for a net transport of ice within Norton Sound to take place out of its entrance and into the Bering Sea.

A high degree of variability was observed: outbound ice velocities range as high as 30 km/day and inbound velocities over 10 km/day were measured. Two dramatic reversals within 48 hours took place with net velocity changes well over 10 km/day.

Often an abrupt transition between the Bering Sea and Norton Sound regimes is observed at the entrance to the sound, giving the appearance that the Bering Sea regime dominates the interaction between the two systems.

Introduction

This report has been prepared in order to aid in assessment of environmental impact occurring as a result of offshore petroleum development within Norton Sound, Alaska. Because spilled oil can become associated with ice in a variety of ways (Stringer and Weller, 1980) there is considerable interest in the residence time and trajectory of ice within, into and from Norton Sound. This report consists of a compendium of ice floe trajectories measured on Landsat images of the Norton Sound vicinity between 1973 and 1980 to aid in this assessment.

Landsat is a polar-orbiting satellite with an orbit determined to provide a 10% overlap between adjacent images at the equator. As a consequence of converging orbit paths with increasing latitude, the overlap at Norton Sound is sufficiently large that a given location on the earth's surface can be imaged on three successive days. Hence it is at least theoretically possible that trajectories representing up to 72 hours' motion may be measured.

Each Landsat repeats a given orbit every eighteen days, allowing the possibility of following ice floes over periods of that duration. During periods when two Landsats are operating, their orbit schedules are arranged such that a floe position could be measured every nine days.

Obviously the determination of floe trajectories depends not only on acquisition of largely cloud-free imagery, but also the ability to recognize particular floes from one image to the next. While this latter requirement does not impose many restrictions from one day to the next, it can be quite difficult to recognize particular floes on images eighteen days apart---even if one attempts to find the pieces of floes which have obviously broken up.

II. Estimated Errors of Measurement

The displacements reported here were measured by sequentially projecting successive Landsat multi-spectral (MSS) images on a transparent screen so that individual pieces of ice could be tracted. (The device used is called a "color-additive viewer" and is manufactured by 1^2S, Inc.) The Landsat images were projected to 1:500,000 scale from 70 mm positive transparencies. Registration of images was provided by superimposing geographical features on the sequential Landsat images. Colvocoresses and McEwen (1973) have shown that the random distortions on a Landsat MSS image have an rms value on the order of 200 m. This is the average error to be expected from the instrumentation. However, the results reported here were based on a visual best fit of two projected images. At the scale used, 1:500,000, 1 km is 2 mm. Some transparencies appeared to superimpose uniformly over the whole Landsat image to well within 1 mm (500 m) while others would show appearent displacements of geographical features of 2 km on one side of a pair of images made to coincide on the opposite side. In these latter cases, a best average fit was obtained. *Since* the geographical features used are located on three sides of Norton Sound, this technique tended to minimize the errors in the center of the area of observation. The errors resulting *from* this latter systematic effect are estimated to be on the order of 1 km. Even though this latter errors would be systematic, it would not be *easy* to describe and correct. For instance, the averaging technique would probably result in displacement errors in a circular pattern with its center at some point within Norton Sound. Because of the difficulty of describing this systematic error, it should be considered a random error, or uncertainty.

This discussion has shown that the largest uncertainty in displacement values is on the order of 1 km and is made up of several components However, the consistency between adjacent displacements achieved on the maps presented here seem to indicate that random errors of measurements were at least less than *or* equal to 500 m.

III. Measured Ice Displacements

The following 20 figures display ice floe displacements measured within Norton Sound between 1973 and.1979. These maps are arranged with eighteen-day displacements (if any) measured for each year, followed by one-day displacements for that year. In cases where particular floes could be tracked for two consecutive intervals, their displacement vectors are joined. Eighteen-day displacements are labeled in terms of interval data while single day displacements are coded by thickness of the displacement vector with successively later days denoted by thicker vectors.

1973 Ice Displacements

Eighteen-day displacements were measured for three successive eighteen-day Landsat cycles between March 21 and May 13. Although no single floes were monitored over this entire period, several were monitored for two successive cycles. , This is the longest period that ice motion could be monitored by means of observations of specific floes.

One day displacement maps for 1973 show motions for:

1) 18-19 March (37 displacements)

19-20 March (46 displacements)

20-21 March (69 displacements)

2) 7-8 April (86 displacements)

8-9 April (32 displacements)

3) 24-25 April (79 displacements)

25-26 April (133 displacements)

26-27 April (48 displacements)

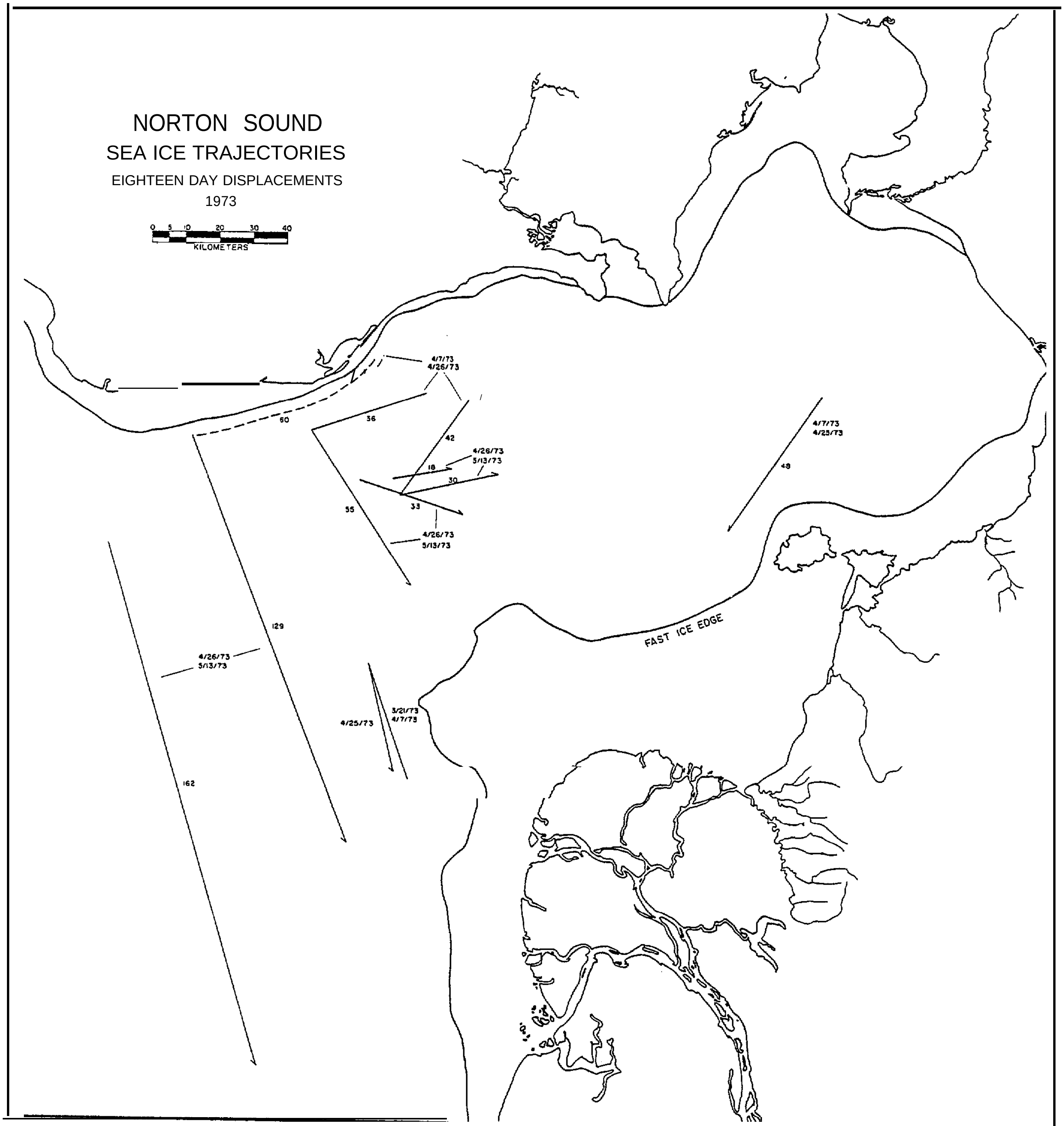


Figure 1 The data shown here span the period March 21 to May 13, 1973. Some ice motions seen here were not measured on any other occasions, Note the floe just off the Yukon Delta which originally moved north and then south, This long-time northward motion appears to be somewhat unusual for this time of year. Between April 26 and May 13 ice within Norton Sound not only remains but moves slightly to the inside of the sound. This is the only observation this far inside. Norton Sound at dates this late in the year and may represent the motion of ice remaining in northern Norton Sound after other ice has been removed.

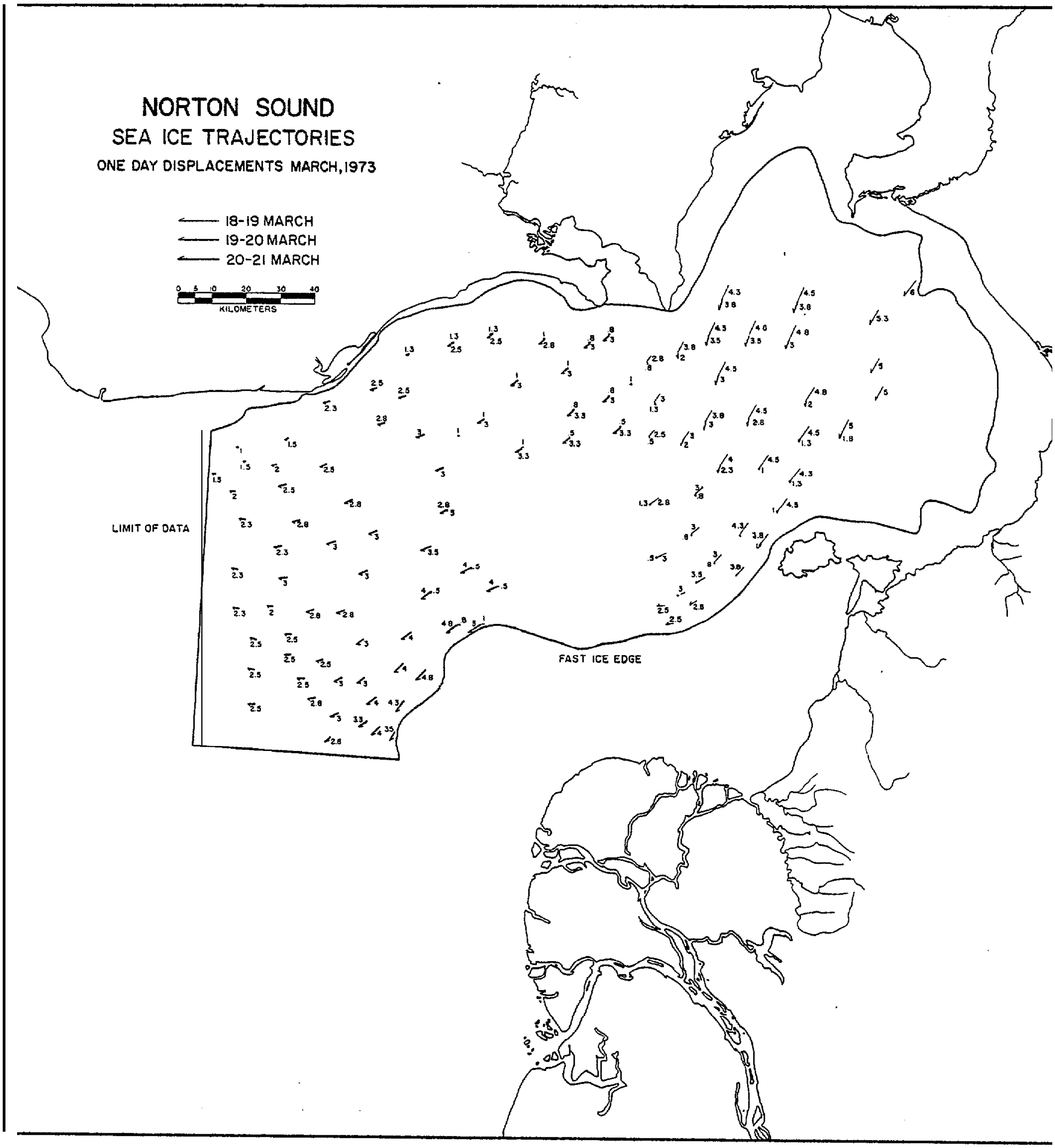


Figure 2 This map, derived from data obtained between March 18 and 21, 1973, shows a rather uniform displacement field throughout Norton Sound. The ice is generally outbound from the sound at rates between 1 and 5 km/day. Note that ice velocities are generally greater at the eastern end of the sound. This is possibly because the ice is thinner in that region and compaction as well as displacement can take place. It is interesting to observe that ice leaving Norton Sound appears to turn slightly northward.

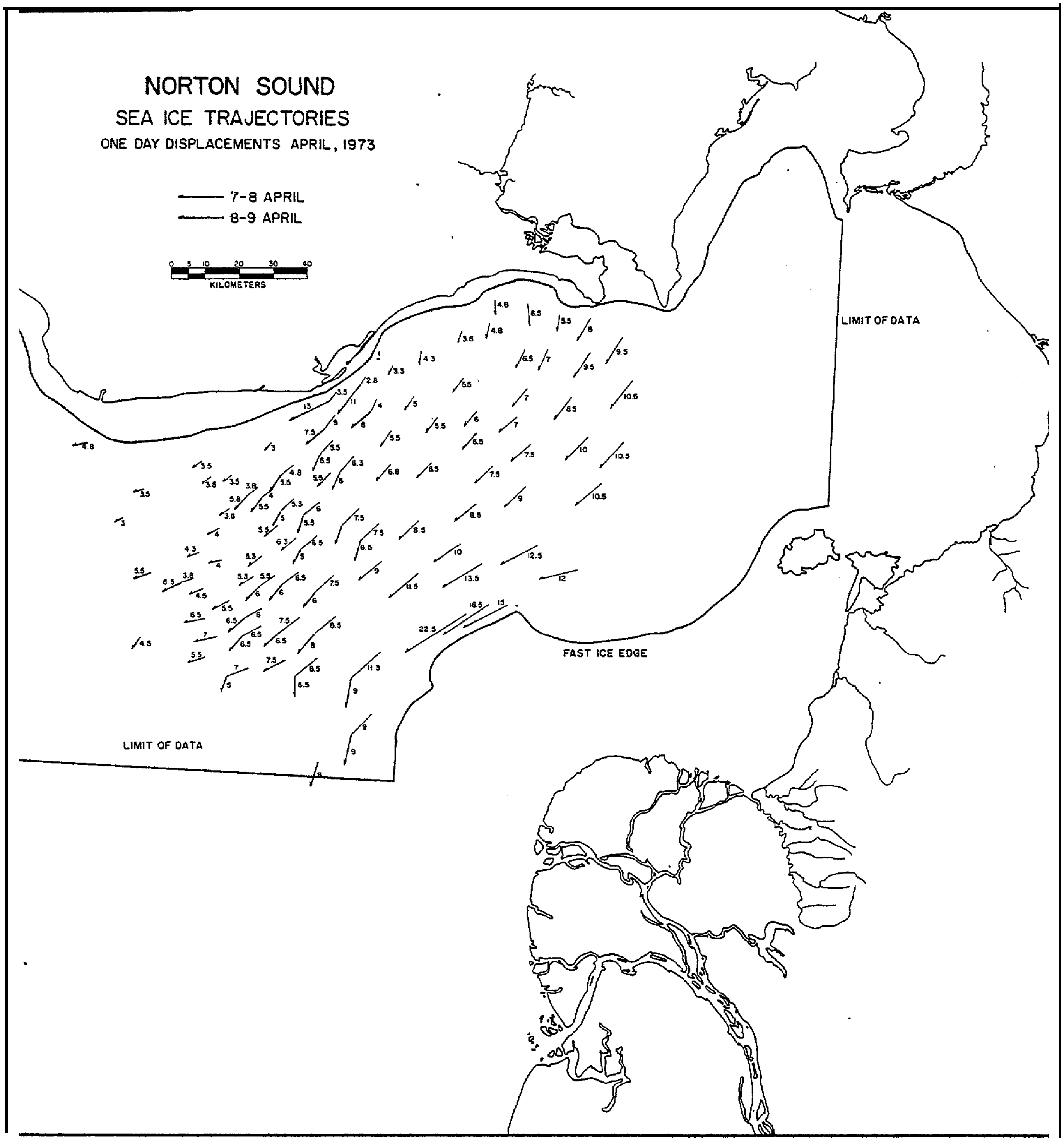


Figure 3 This map exhibits displacements measured between April 7 and 9 1973, in central and western Norton Sound. Ice motions on both days were outbound from the sound at speeds ranging from 3 to 22 km/day. The greatest speeds were observed just seaward of the fast ice edge located on the Yukon prodelta. There is a general decrease of displacement from east to west which is thought to result at least in part from compaction of the relatively thin ice in the eastern portion of the sound.

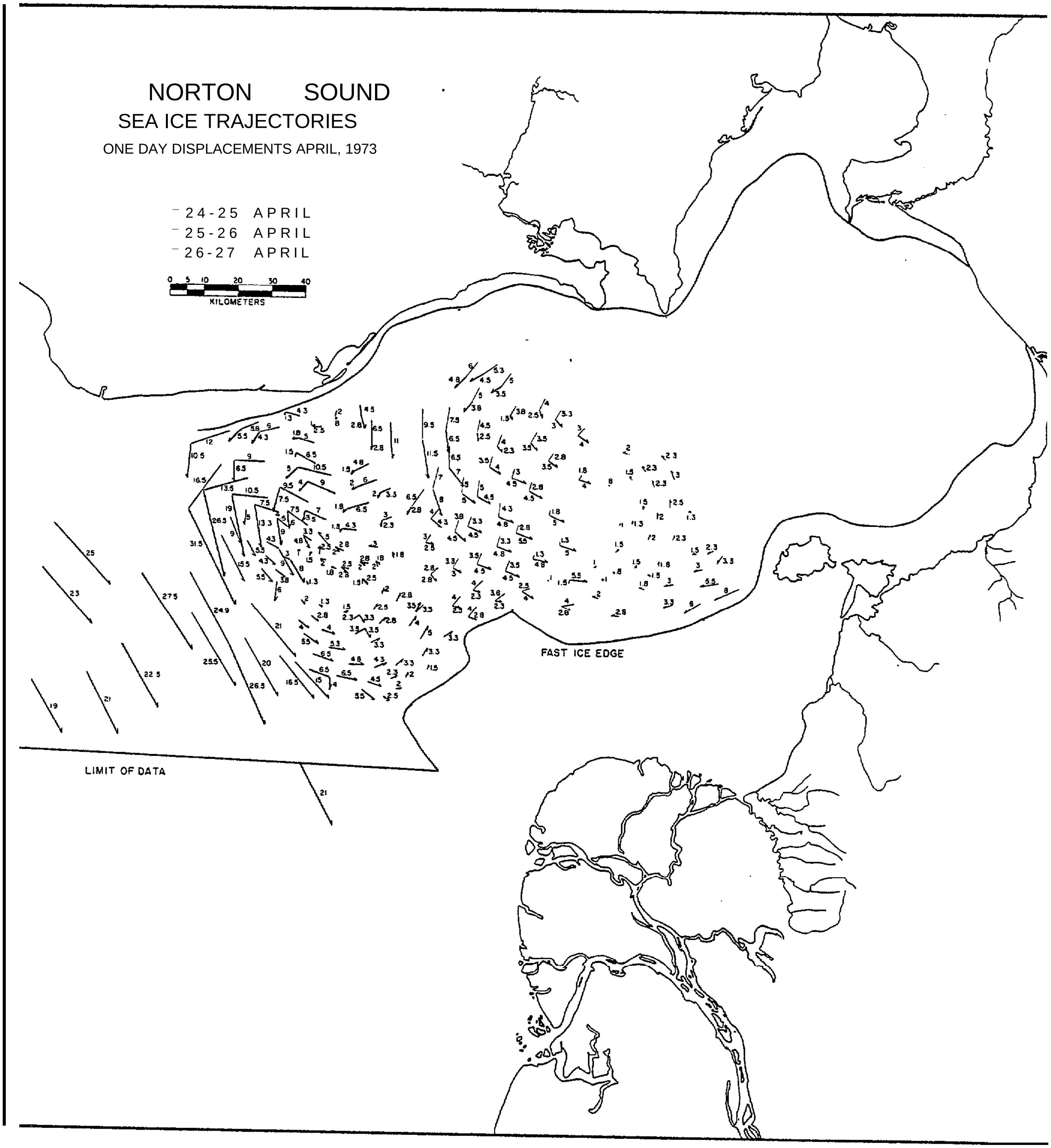


Figure 4 Shown here are Norton Sound ice displacements observed between April 24 and 27, 1973. During this period the ice appears to be partici-pating in two counterclockwise (looking down) gyres. At the same time, the ice in the adjacent Bering Sea is streaming past the entrance to Nor-ton Sound on a nearly due south heading at speeds ranging up to 27 km/day One piece of Norton Sound ice which has entered this stream from the top of the western gyre has a displacement of 31 km in one day.

1974 Ice Displacements

Eighteen-day displacements were measured for the period April 2 to April 21.

One-day, displacements were measured for:

1) 8-9 February (39 displacements)

2) 14-15 March (42 displacements)

15-16 March (63 displacements)

3) 1-2 April (31 displacements)

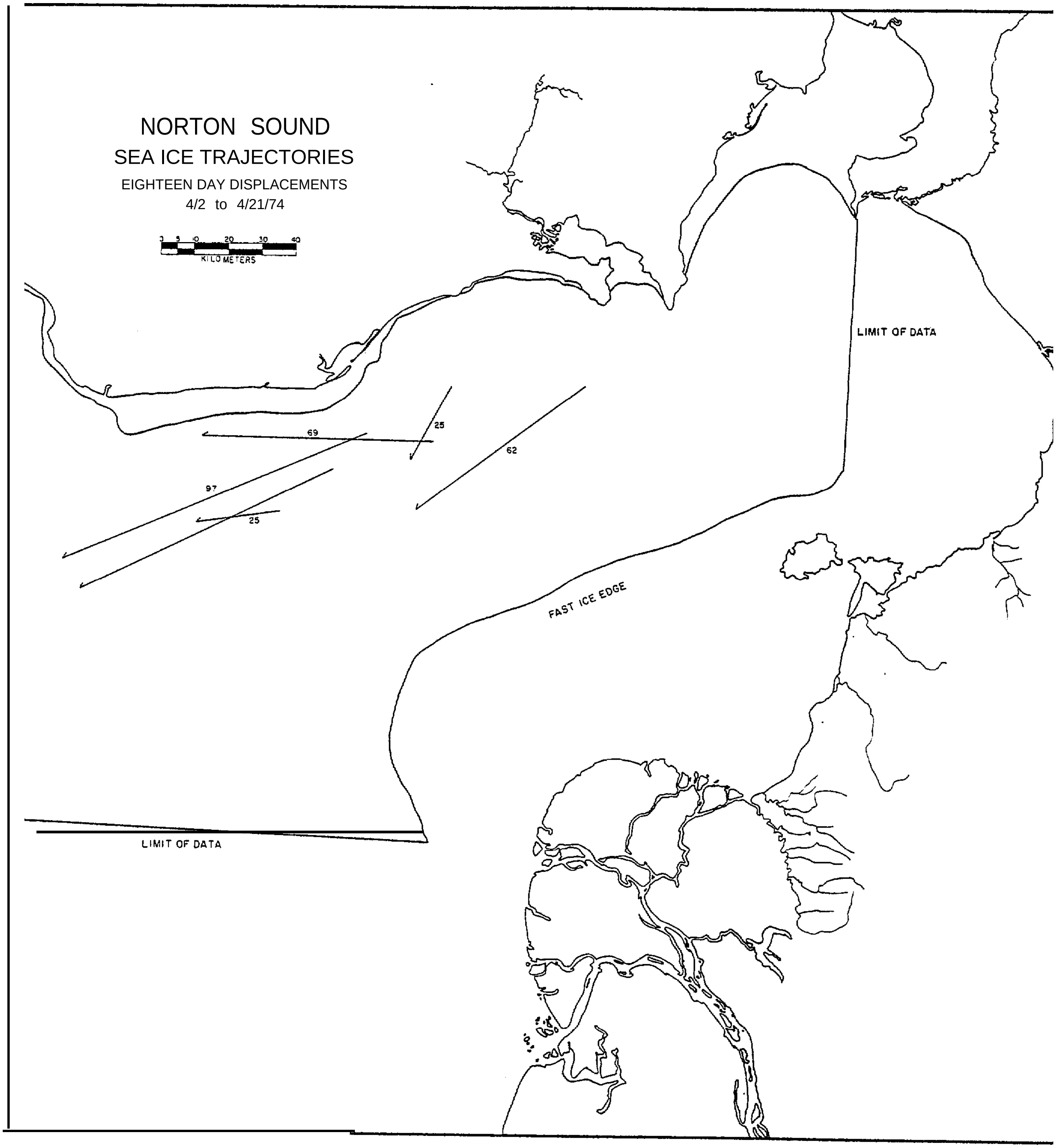


Figure 5 Eighteen-day displacements in 1974 were only measured between April 2 and 21. *Note* that these displacements do not form a uniform vector field as do the one-day displacements. Speeds of nearby floes vary significantly and tracks of floes cross. This behavior suggests that during the 18-day interval general behavioral patterns took place resulting in the displacement pattern seen here. Note that the largest displacement shown here, 97 km, corresponds to a daily speed of 5.4 km/day---not inconsistent with the range of daily displacements observed.

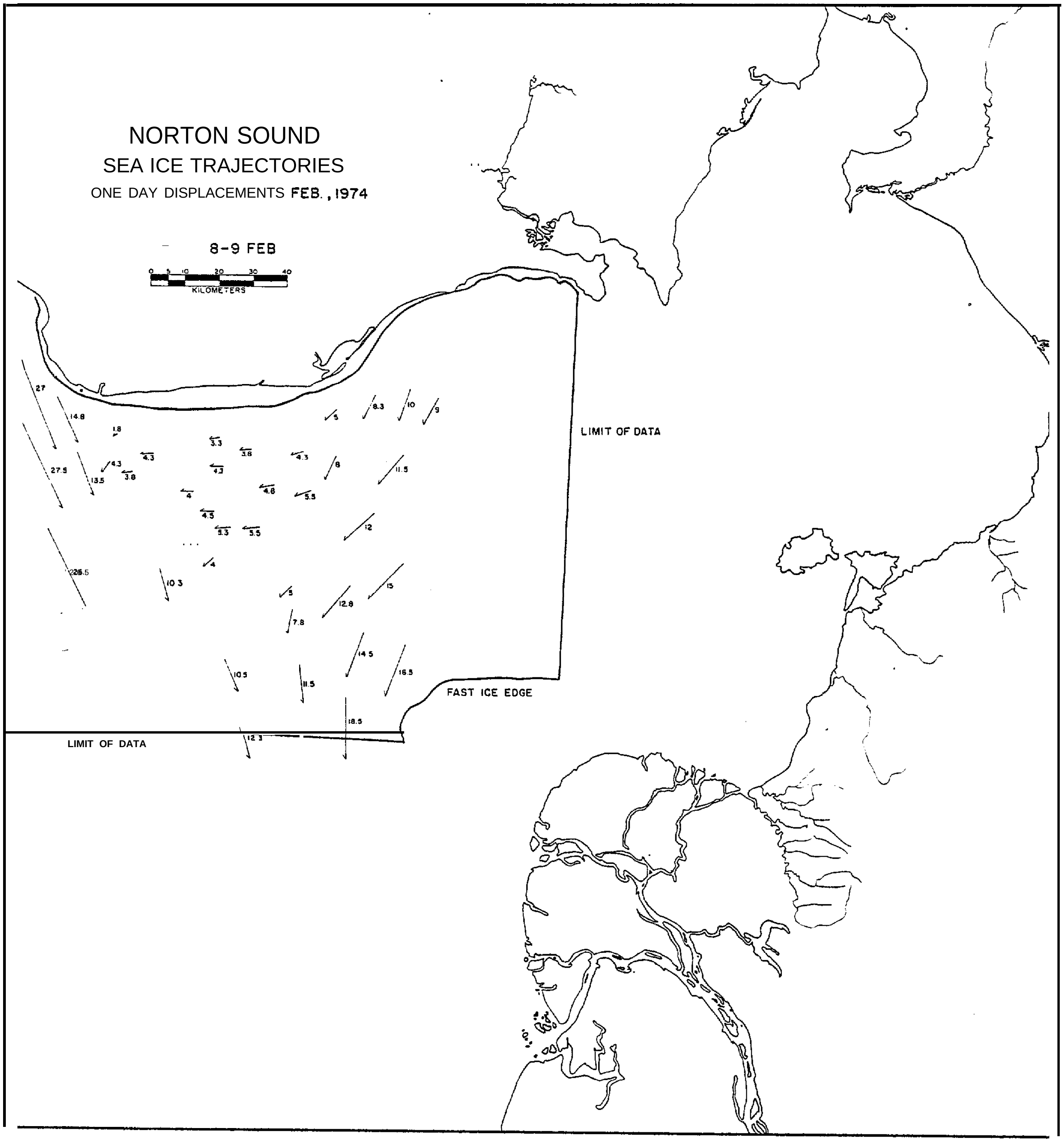


Figure 6 This map shows ice floe displacements in western Norton Sound measured between February 8 and 9, 1974. Although not forming a uniform vector field, ice is generally flowing out from Norton Sound. As is often the case when ice is outbound, the highest speeds are found just seaward of the fast ice boundary off the Yukon prodelta. Here these speeds are in the 16-18 km/day range. Bering Sea ice is moving past the entrance to Norton Sound at speeds on the order of 27 Ian/day.

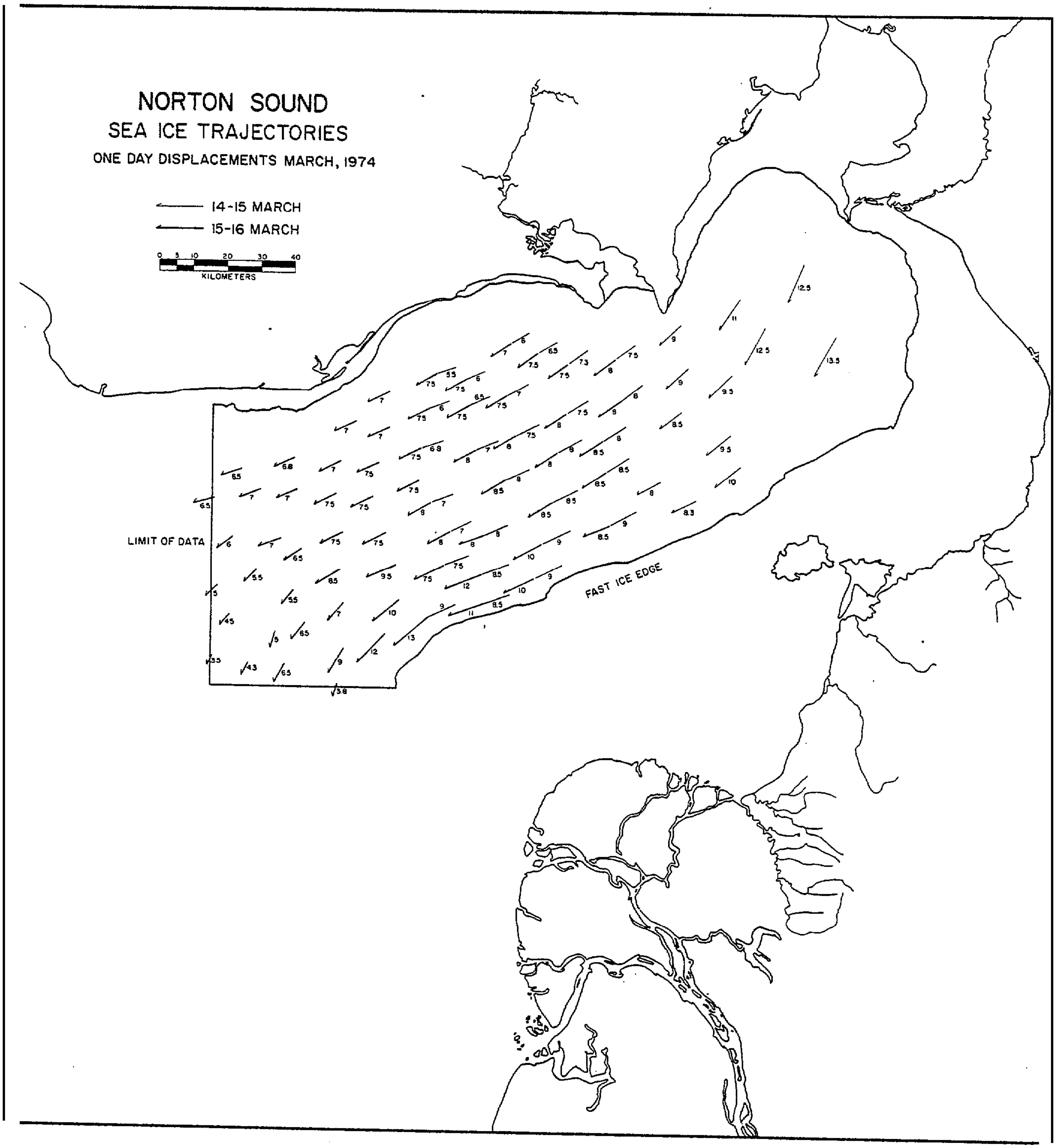


Figure 7 This map was derived from Landsat images obtained between March 14 and 16, 1974. Two-day displacements were measured for some floes in central Norton Sound. The generally constant values found for these floes from one day to the next suggest that the conditions mapped here were constant over the two-day period. Note that higher speeds are measured as the eastern end and southern side of the sound as is often the case when the ice displacements form a uniform vector field. Note also that displacements are smallest where the ice is turning to join the ice in the Bering Sea.

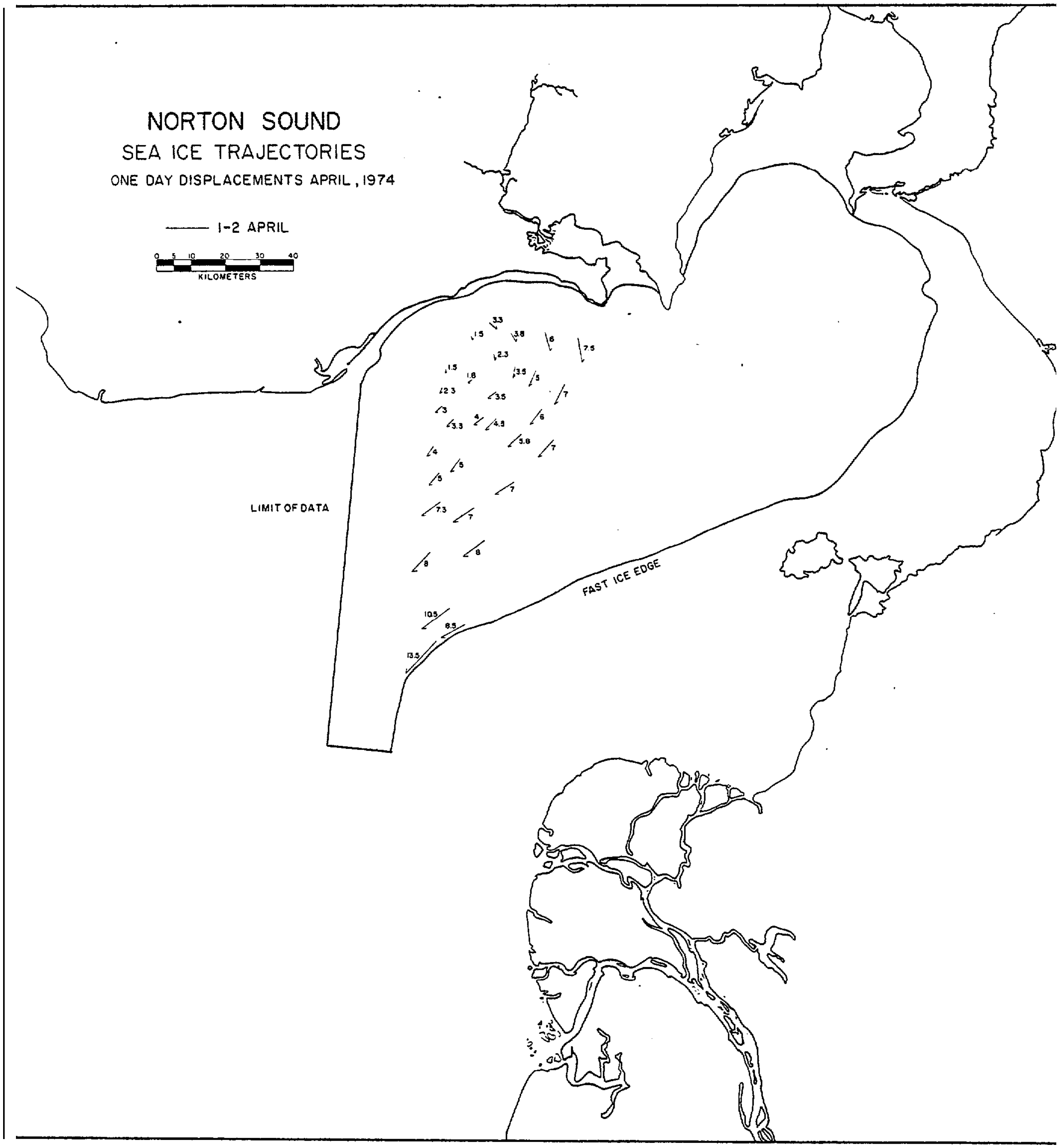


Figure 8 This map shows ice floe displacements measured between April 1 and 2, 1974. Although not many displacements were measured at least part of the general pattern seen on other maps is seen here again: The largest displacements are measured just seaward of the fast ice edge located on the Yukon River prodelta. Here these displacements are as great as 13 km/day.

1975 Ice Displacements

Eighteen-day displacements were measured for the period May 13 to May 31.

One-day displacements were measured for:

7-8 April (32 displacements)

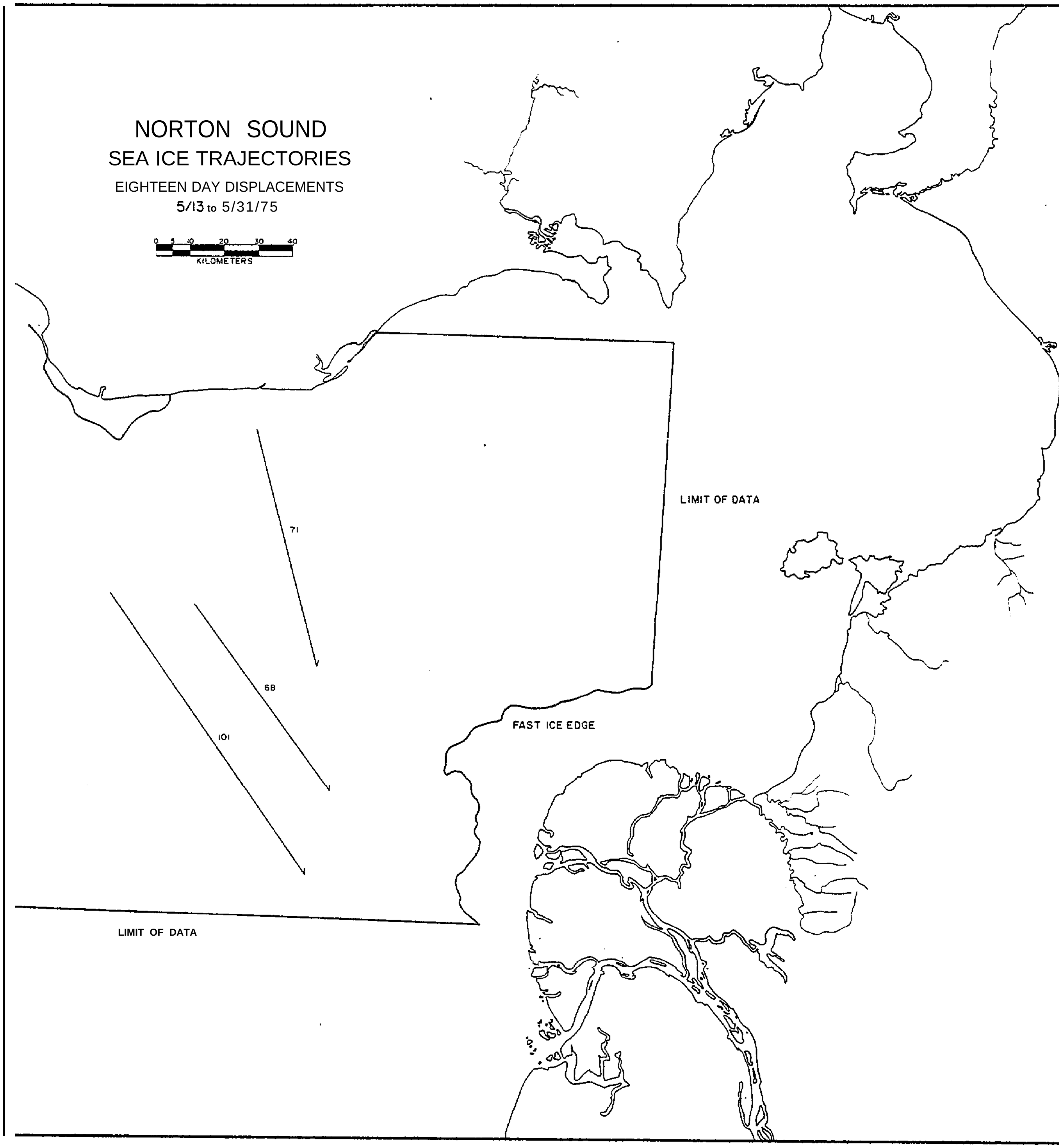


Figure 9 This map shows 18-day displacements measured between May 13 and May 31, 1975. The displacements shown here are generally outside Norton Sound and do not yield much information about motions of Norton Sound ice. However, they do show that ice can be southbound at these late dates, showing that the generally held concept that Bering Sea ice becomes northbound at this time of the year is not universally true.

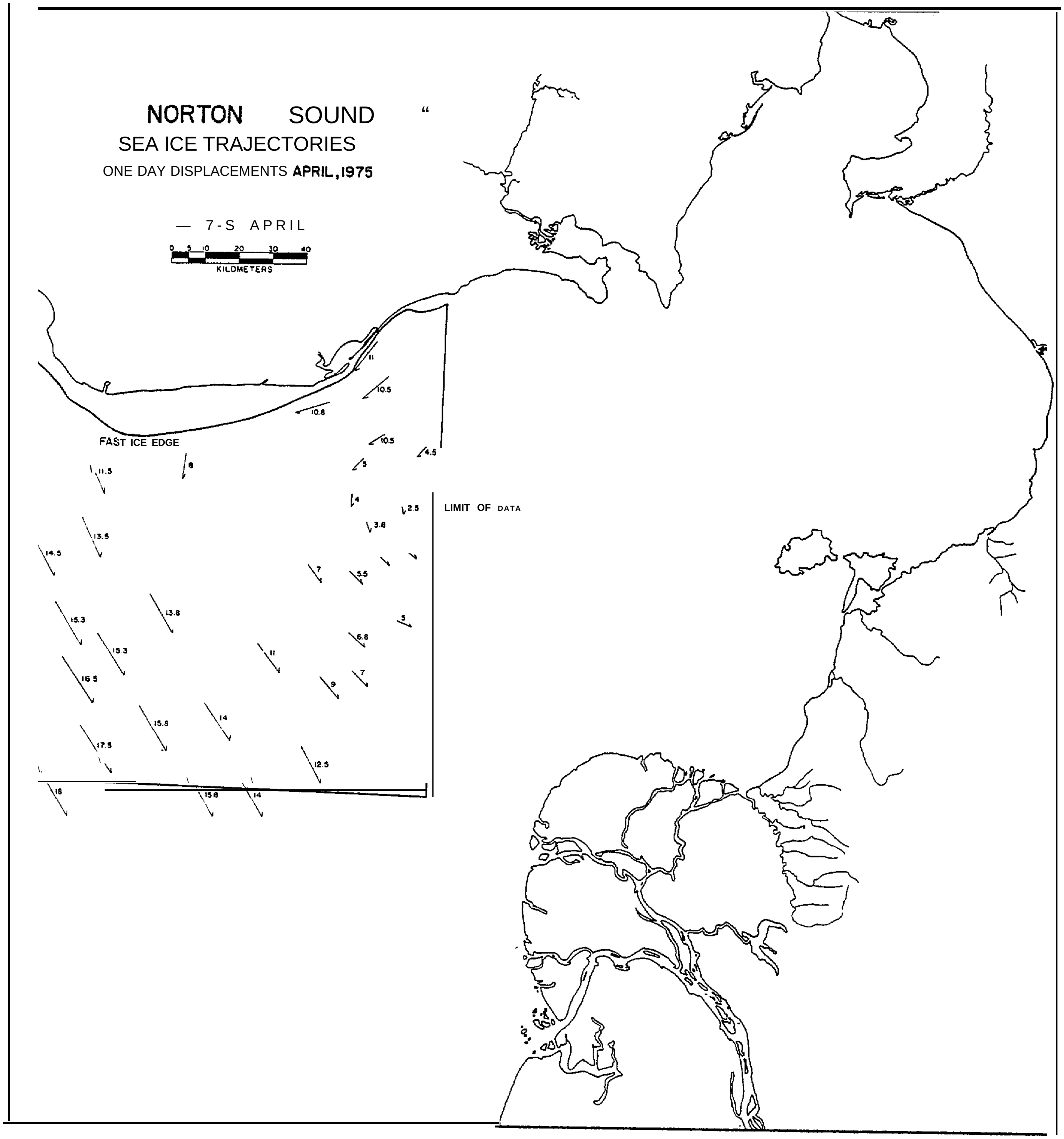


Figure 10 This map shows floe displacements in western Norton Sound and the adjacent Bering Sea. There is fairly strong evidence of a counterclockwise gyre of ice in Norton Sound. Bering Sea ice is moving past the entrance to Norton Sound with a heading azimuth nearly due south. The Bering Sea displacements are as great as 18 km/day. One has the impression that the Norton Sound gyre is driven by the Bering Sea ice moving past the entrance to the sound.

1976 Ice Displacements

No eighteen-day displacements were measured for this year.

One-day displacements were measured for:

1) 25-26 February (67 displacements)

2) 12-13 March (62 displacements)

13-14 March (45 displacements)

14-15 March (25 displacements)

3) 29-30 March (19 displacements)

30-31 March (32 displacements)

4) 17-18 April (58 displacements)

18-19 April (78 displacements)

19-20 April (40 displacements)

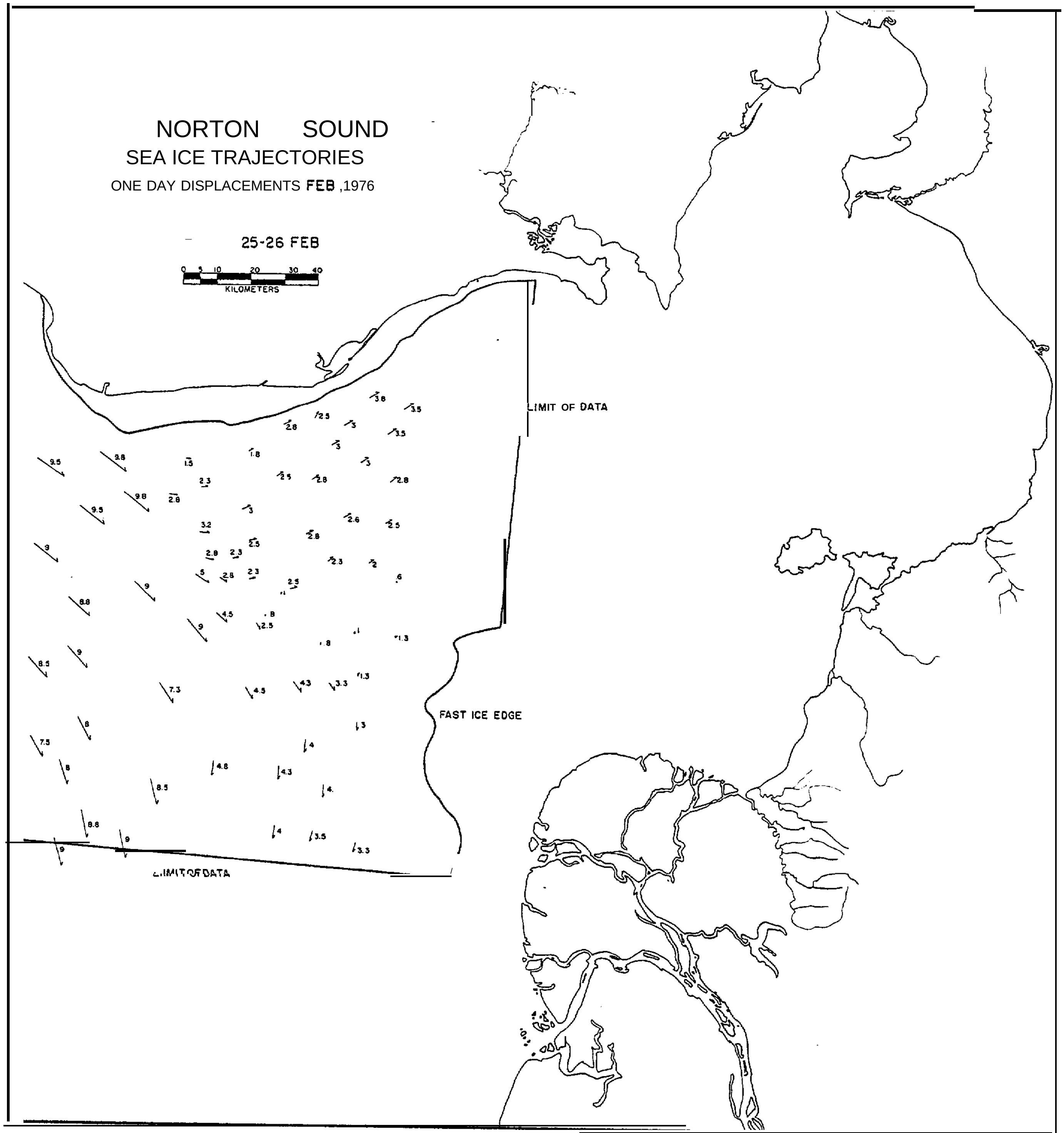


Figure 11 This map shows ice displacements in Norton Sound and the adjacent Bering Sea between Feb. 25 and 26, 1976. Here ice is generally being advected into Norton Sound and no gyre is taking place. Note that the Bering Sea ice heading angle is changing as it moves past the entrance to Norton Sound. This gives a greater impression of ice actually being pushed into Norton Sound than in the cases where the gyre was formed. In those cases the Bering Sea ice appeared to be merely moving past the entrance on a more or less constant heading.

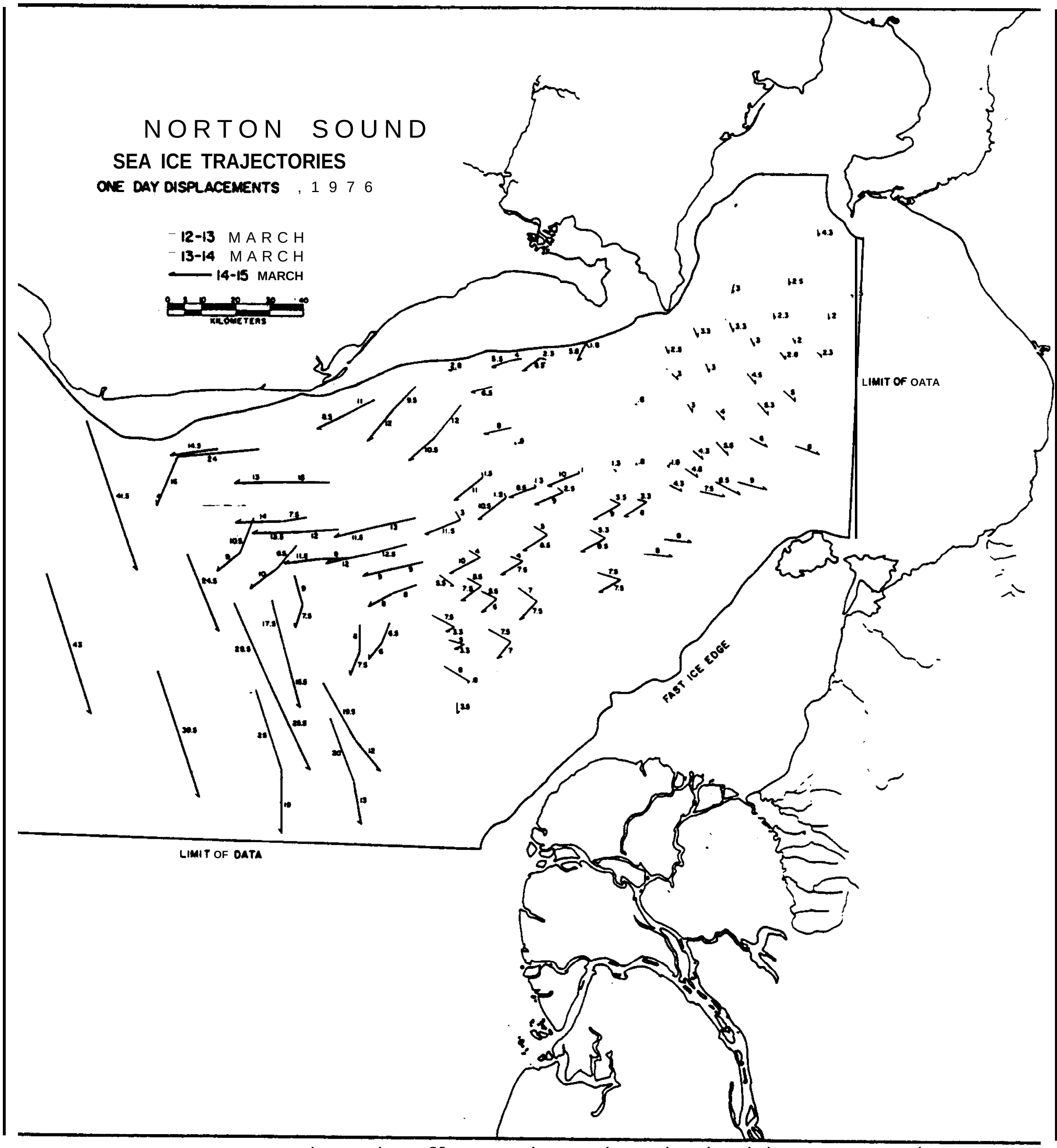


Figure 12 This map shows ice floe trajectories obtained between March 12 and 15, 1976. The situation shown appears somewhat confused: Apparently, between the 12th and 13th, ice in the eastern end of the sound was moving inward and the ice in the far eastern end was participating in a counterclockwise gyre. On the two subsequent days, ice within Norton Sound was outbound. It is interesting to note that between the first and second days some floes actually reversed the general inbound/outbound direction of their motion, traveling over 7 km each day in nearly opposite directions. Bering Sea ice was monitored only between the second and fourth days. The displacements measured were as great as 43 Ian/day. Note the abrupt transition between Norton Sound and Bering Sea displacements, both in terms of heading angles and displacements.

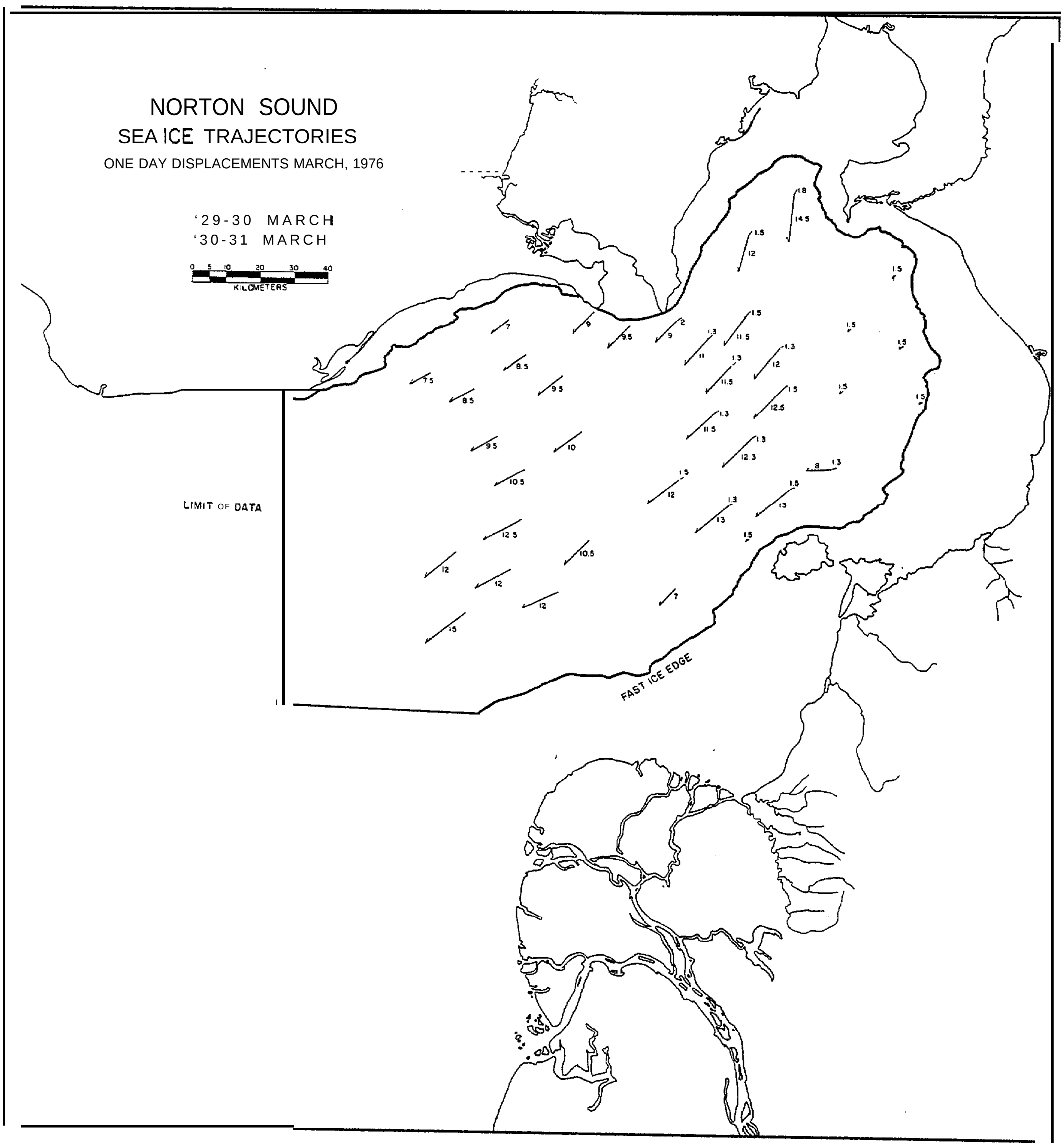


Figure 13 This map shows Norton Sound ice floe trajectories observed between March 29 and 31, 1976. In this case there was a considerable difference in displacements between the first and second days (on the order of a factor of ten) again showing the considerable degree of variation possible from one day to the next, However, in both cases, ice motions are generally outbound. On the second day displacements as great as 15 km were observed. Again as in other cases of general outbound ice motion the highest speeds were observed in the vicinity of the fast ice located off the Yukon River prodelta.

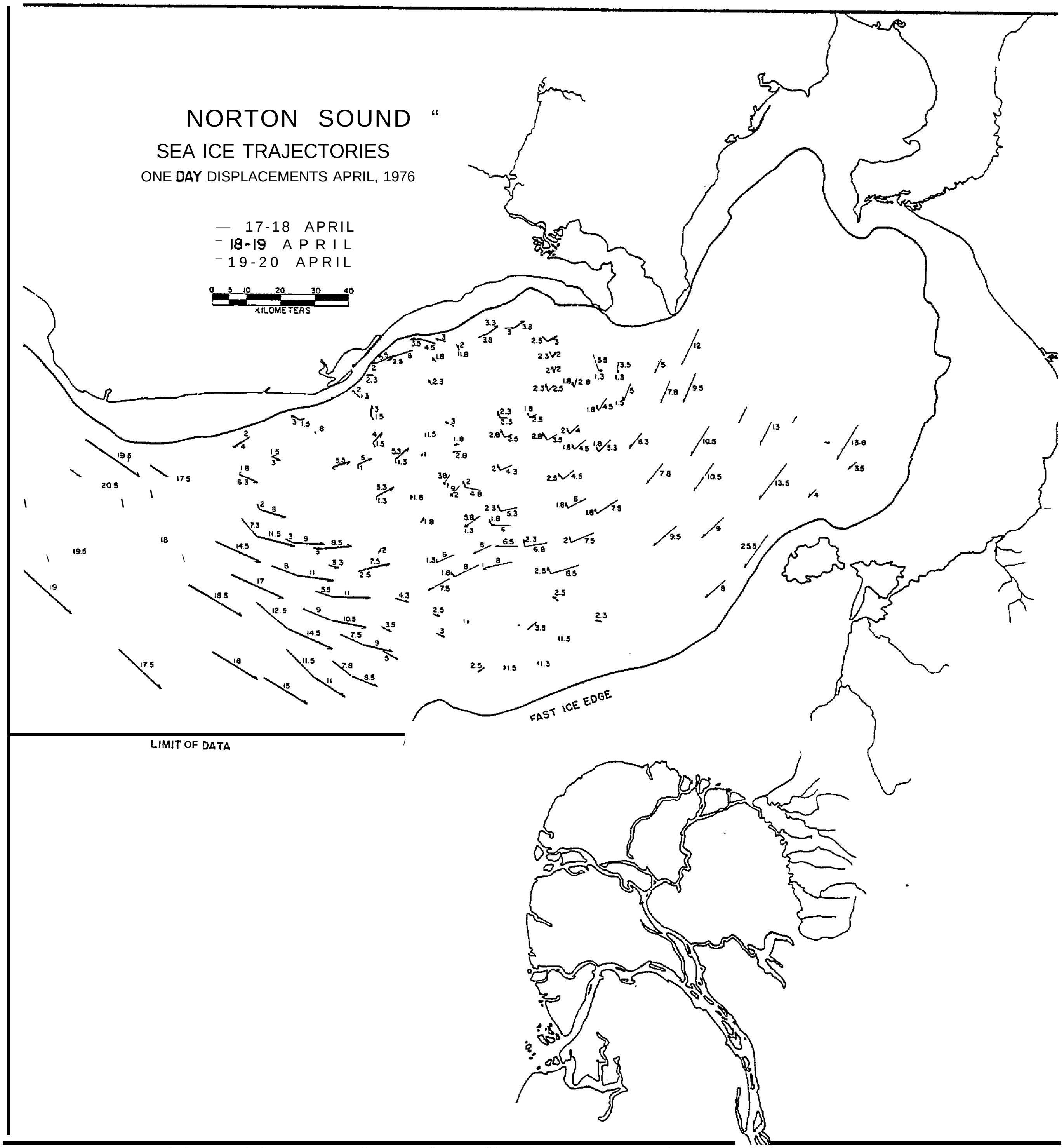


Figure 14 This map shows ice displacements observed between April 17 and 20, 1976. The ice motions seen here appear to illustrate a transition from ice following an outbound behavioral mode to an inbound mode. On the first pair of days ice in eastern end of Norton Sound was monitored. At that time the ice appeared to be flowing uniformly from Norton Sound. On the second day many floes appear to undertake an abrupt 90° turn to the north and undergo a small displacement in that direction. Most third day displacements observed within Norton Sound are directly into the sound. Bering Sea floe displacements are rather interesting. The ice appears to be driven into Norton Sound, being slowed down considerably in the process. Hence this occasion appears to show a direct confrontation between the Norton Sound and Bering Sea ice regimes.

1977 Ice Displacements

Eighteen-day displacements were measured for the period April 14 to May 2.

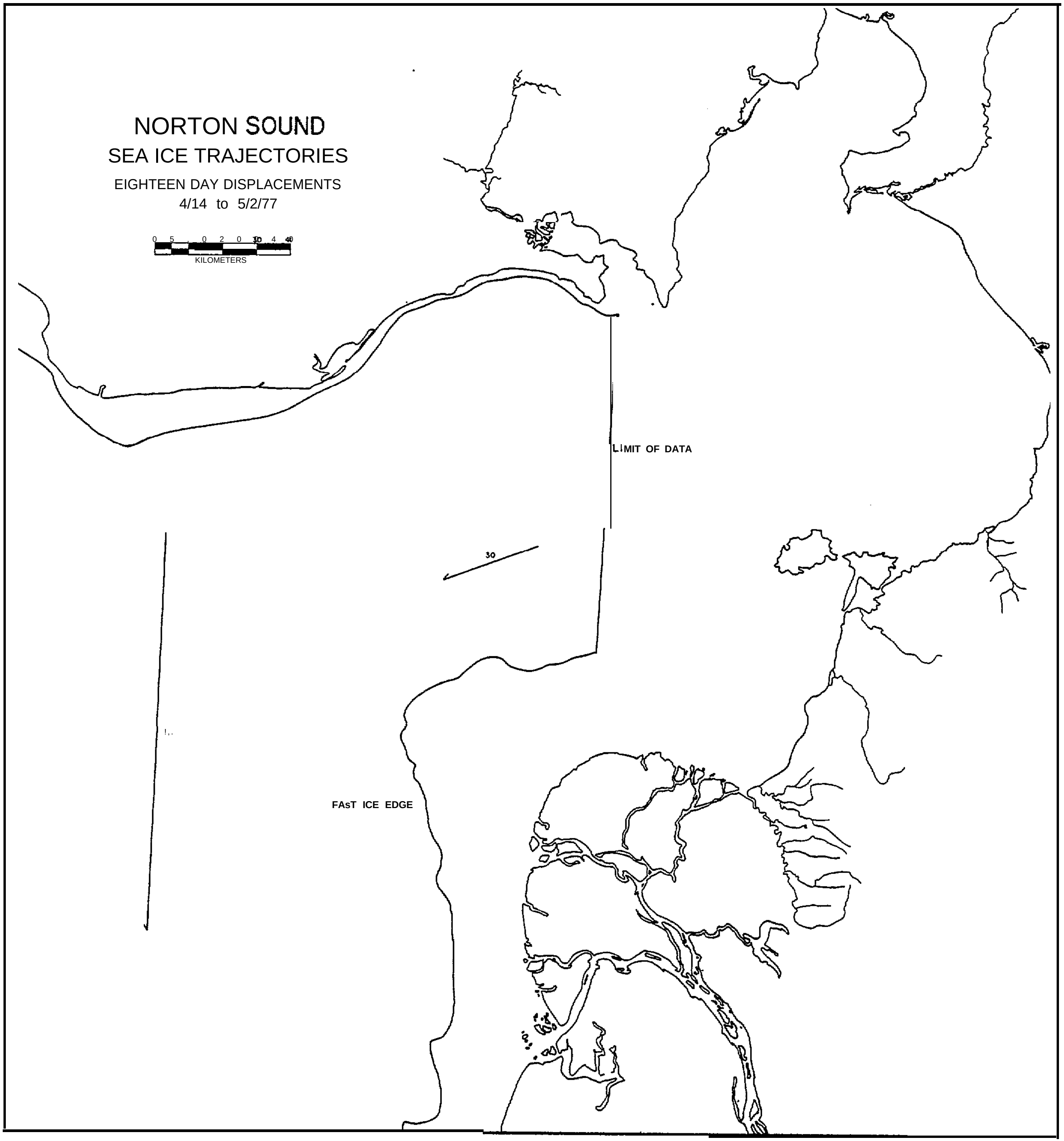
One-day displacements were measured for the periods:

1) 24-25 March (41 displacements)

   25-26 March (58 displacements)

2) 13-14 April (49 displacements)

   14-15 April (36 displacements)



<u>Figure 15</u> This map shows ice displacements measured between April 14 and May 2, 1977. Only two displacements were measured; one in Norton Sound, the other in the adjacent Bering Sea. The Norton Sound displacement corresponds to an average daily motion of less than 2 km/day and shows that Norton Sound ice can be rather stagnant at this time. Even the Bering Sea displacement measured during this time is rather small; an average of 6.5 km/day to the southwest.

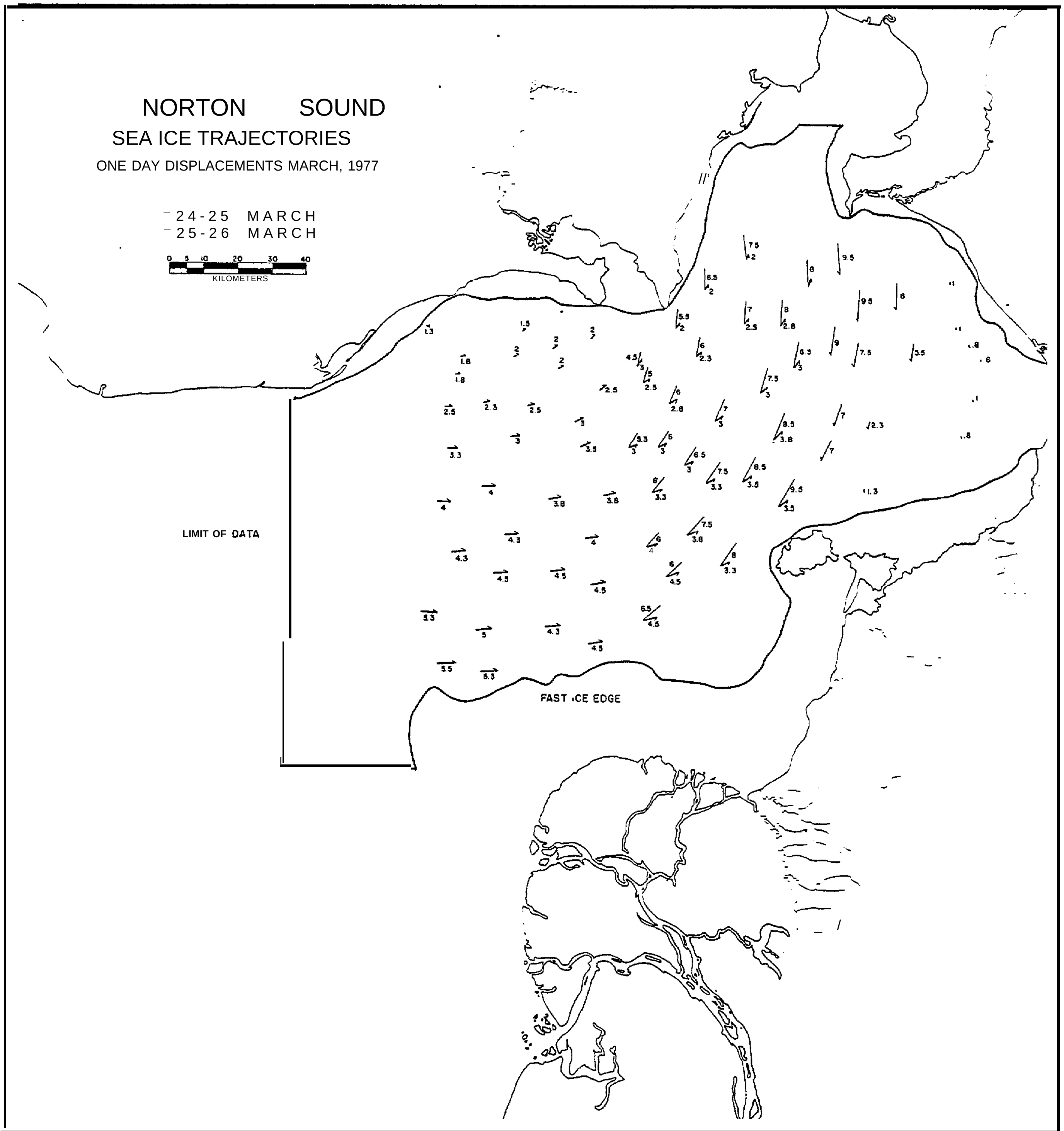


Figure 16 This map shows Norton Sound displacements measured between March 24 and 26, 1977. The motions shown here illustrate clearly the abrupt transition possible between the outbound and inbound modes of Norton Sound pack ice: on the first day, outbound ice motions on the order of 7-9 km were measured, while on the second day inbound ice displacements on the order of 3-5 km were measured. Floes monitored for two consecutive one-day intervals made an almost complete reversal from one day to the next. Note that just as the outbound velocities are greatest along the southern boundary of the Norton Sound pack ice, so are the inbound velocities there the greatest among those observed.

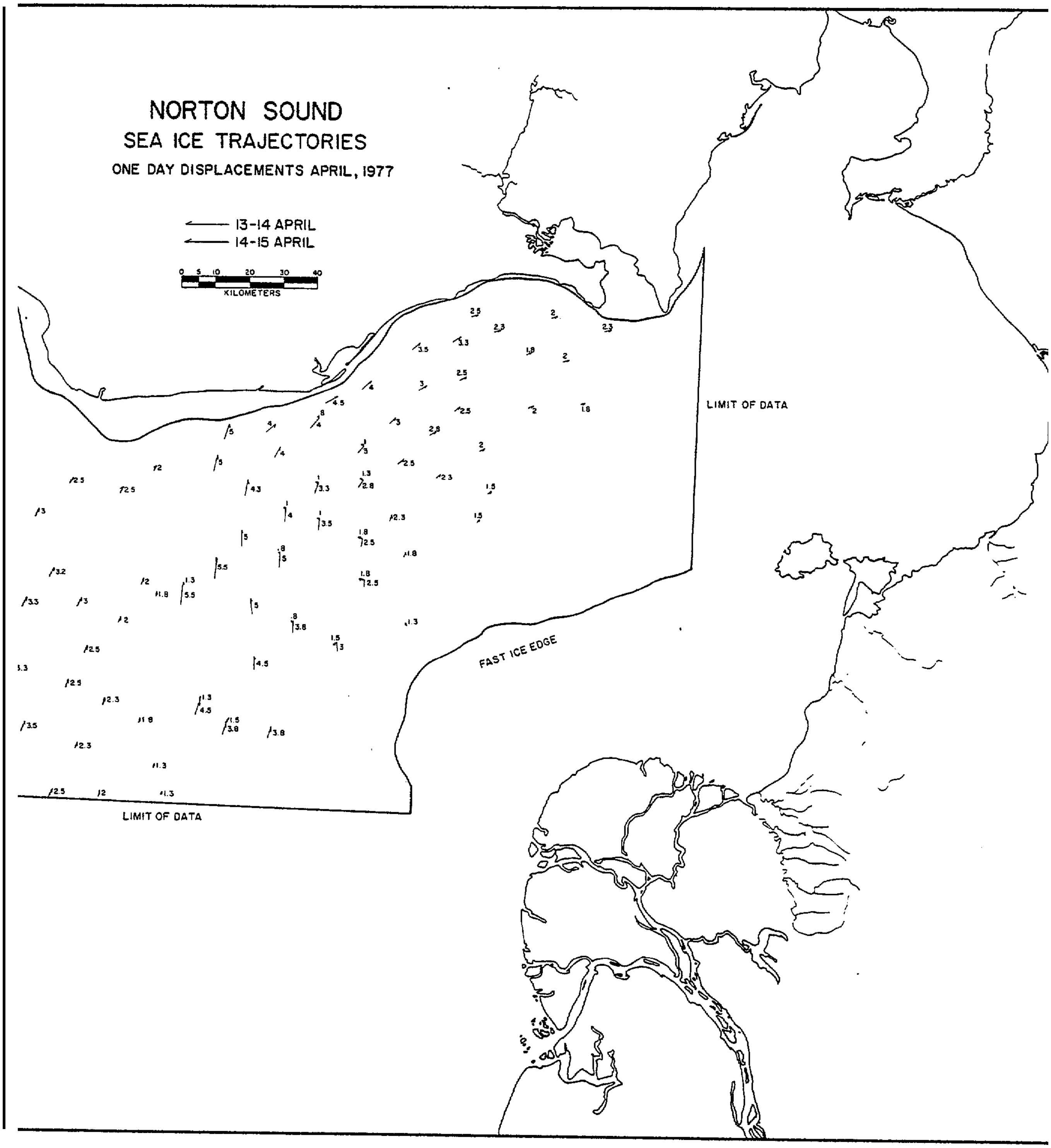


Figure 17 This map shows Norton Sound ice displacements measured between April 13 and 15, 1977. On the first day the ice motions were clearly inbound, with the greatest velocities measured along the northern boundary of the sound, Displacements measured for the second day continued to be inbound in the entrance to the sound, but showed signs of an abrupt halt farther toward the central region of the sound. It is interesting to observe that Bering Sea ice appears to be driven into Norton Sound in this case from the southwest.

1978 Ice Displacements

No eighteen-day displacements were measured for this year.

One-day displacements were measured for:

1-2 March (25 displacements)

2-3 March (59 displacements)

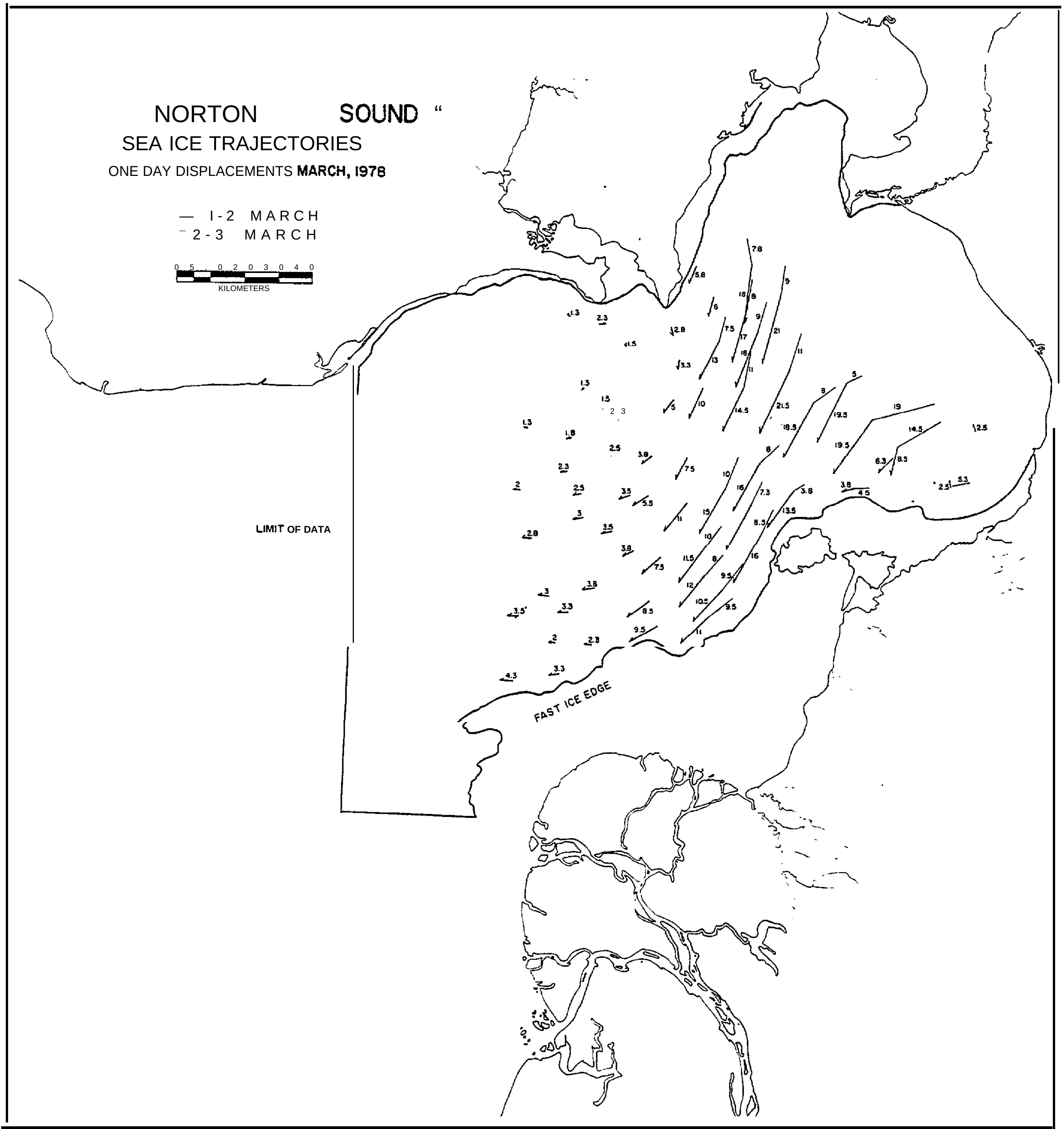


Figure 18 This map shows Norton Sound ice displacements measured between March 1 and March 3, 1978. Here a large variation in displacements can be seen from the eastern portion of the sound to the central region. Although the ice motions are generally outbound, a small gyre exists in the north central portion of the vector field. The ice in the eastern portion of this map is quite thin and is subject to compaction mechanisms including minor ridging and rafting.

1979 Ice Displacements

No eighteen-day displacements were measured for this year.

One-day displacements were measured for:

1) 15-16 February (35 displacements)

16-17 February (47 displacements)

2) 24-25 February (17 displacements)

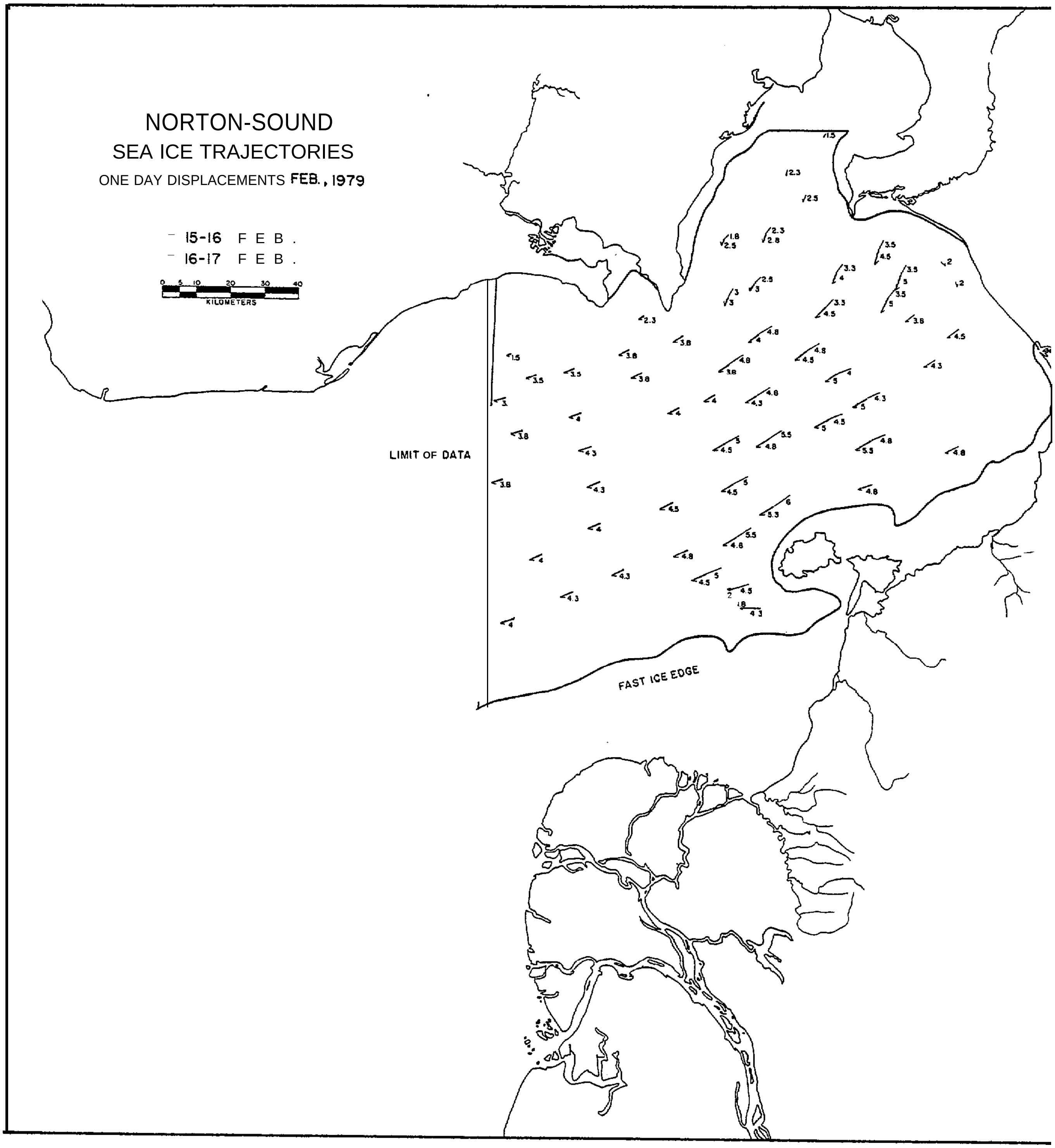


Figure 19 This map shows Norton Sound ice trajectories between Feb. 15 and 17, 1979. The floes imaged all three days show considerable uniformity in displacement from one day to the next. Again, the most southerly displacements appear to be the largest.

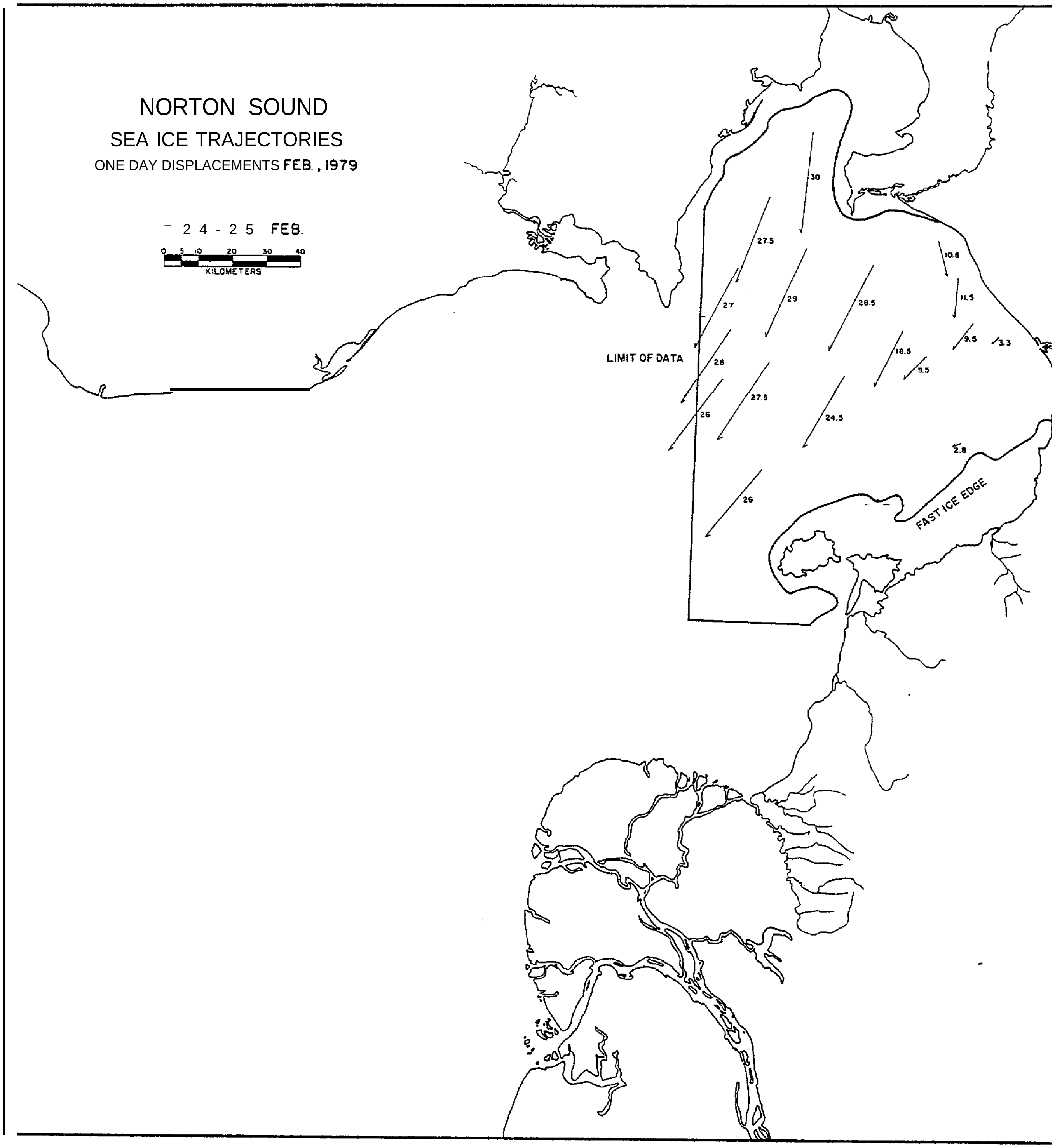


Figure 20 This map shows Norton Sound ice displacements measured between Feb. 24 and 25, 1979. The displacements observed here are among the largest seen in Norton Sound and range up to 30 km/day (30 km/sec). Again, uniform outbound ice motion is shown.

Influence of Cloudiness on Selection of Data

Obviously satellite imagery dependent on the visible portion of the spectrum will not be available during cloudy periods. This selection effect raises the question of the general applicability of data derived by this means. It can be argued that cloudiness is associated with barometric low pressure systems and therefore ice conditions during lows are not monitored.

In order to test this hypothesis, a running pressure chart for Nome was analyzed for those periods when sea ice trajectories were measured. The events were divided into four categories of barometric pressure variation at Nome on the north side of Norton Sound:

1) Relative high
2) Pressure increasing from relative low
3) Relative low
4) Pressure decreasing from relative high

The results of this analysis are shown on Table 1 (Page 33)

In terms of pressure variations at Nome, the Landsat observations seem to be nearly evenly distributed. While this analysis by no means shows that cloudiness is not associated with unique meteorological effects influencing ice motion, it does show that in terms of barometric pressure variations the data is not highly skewed in terms of any particular pressure situation. Perhaps a better parameter with which to gauge the influence of cloudiness on ice motion would be the geostrophic wind. This would require a much more detailed analysis which may be possible in the future.

Observation Period	Sense of Barometric Pressure Variation Relative High	High going Low	Relative Low	Low going High
3/18-21/73		X		
4/7-9/73			X	
4/24-27/73		X		
2/8-9/74			X	
3/14-16/74		X		
4/1-2/74			X	
4/7-8/75				
2/25-26/76	X			
3/12-15/76 – –	X			
3/29-31/76			X	
4/17-26/77				
4/13-15/77	X			
3/1-3/78	X			
2/15-16/79		X		
2/24-25/79				X
Totals	4	4	4	3

Table 1. Categorization of Norton Sound ice movement observations in terms of sense of barometric pressure variation at Nome.

OBSERVATIONS

The main purpose of this report is to display the ice displacement maps and discuss the uncertainties involved in measurements and data availability. Detailed discussions will follow. However, several general observations can be made at this time:

1. Ice within Norton Sound behaves, in general, according to three behavorial modes: ice outbound, ice inbound and ice gyre.

2. The outbound mode appears most frequently, supporting the generally-held thought that ice formed in Norton Sound is fed into the Bering Sea.

3. The inbound mode can correspond to both northbound or southbound Bering Sea ice.

4. The displacements observed during the inbound mode are generally smaller than those of the outbound mode, further supporting the thought that the net ice motion is outbound.

5. Bering Sea ice often moves past the entrance of Norton Sound at speeds 3 to" 4 times greater than the simultaneous Norton Sound ice motion speeds. In the cases that this phenomenon coincides with outbound modes, the Norton Sound ice accelerates upon joining the stream of Bering Sea ice. The line marking the location of this acceleration runs roughly across the entrance to Norton Sound.

6. For periods as long *as* 36 days, ice within northern Norton Sound can remain relatively motionless. (See the 1973 18-day displacements) .

7. Often, in the case of outbound modes, the greater ice speeds near the entrance to the sound are measured on the south side, just off the Yukon River prodelta.

8. Across the length of the sound the greatest displacements are found at the eastern end.

9. Ice motions within Norton Sound can easily reverse from one day to the next.

CONCLUSIONS

1. Ice behavior in Norton Sound should not be considered to be a simple extension of the motion in the, adjacent Bering Sea. Although at times the outbound mode appears to be coupled with southbound Bering Sea ice, the inbound mode can also occur when Bering Sea ice is southbound. Furthermore, Norton Sound ice seldom flows directly into the Bering Sea. Often the Norton Sound ice appears to be held back by the stream of Bering Sea ice flowing past the entrance to Norton Sound. It would be more correct to consider the Norton Sound and Bering Sea ice regimes as coupled systems with the Bering Sea as dominating the relationship.

2. The movement of ice from and within Norton Sound is highly variable. Outbound displacements of 10-15 km/day are not unusual, but probably represent the high end of the spectrum of velocities. On the other end of the velocity spectrum, ice has been shown to linger up to 36 days near the entrance to the sound. Displacement reversals can take place from one day to the next and besides the inbound and outbound modes, even gyres of ice floes are possible. Taken together these observations indicate that although the general motion of ice is toward the entrance, a great deal of loitering and mixing can take place. This conclusion is particularly important when considering the trajectory of an oil spill associated with the Norton Sound ice pack.

ACKNOWLEDGEMENTS

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