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PHYSICAL OCEANOGRAPHIC INVESTIGATIONS IN THE BERING SEA MARGINAL ICE ZONE*

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by

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*This document is intended as a stand-alone attachment describing physical oceanographic studies carried out in support of OCSEAP Research Unit #87, and comprises part of a draft final report to the University of Washington and to the OCSEAP program for this Research Unit.

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2.1. INTRODUCTION

2.1.1. Summary

A physical oceanographic field program has been carried out in the Bering Sea marginal ice zone (MIZ) as part of an integrated research effort addressing air-ice-water interactions in the MIZ and relating these interactions to fate and transport of OCS-related pollutants. As part of this field program, water temperature and salinity observations have been obtained from the Bering Sea MIZ during autumn (November) 1980 and mid-winter (February-March) 1981. Moored current observations were also obtained from two locations in the MIZ during the corresponding over-winter (November 1980 - June 1981) period. This report describes and discusses the temperature, salinity and current observations and relates the conditions summarily to past work and to current hypotheses concerning regional processes.

2.1.2. Background

Little information was available, prior to this study, concerning physical oceanographic processes in the Bering Sea MIZ. This lack of information was due in large part to logistical difficulties inherent in winter field activities in the region. Rigorous speculation on physical oceanographic processes in the Bering MIZ was initiated by Muench and Ahlnäs' (1976) observation that the MIZ was the locus of ice melting for the Bering Sea. This realization led in turn to speculation concerning methods by which heat to melt the ice might be supplied to the MIZ; a crude regional heat budget was computed by Muench and Ahlnäs. The realization also pointed out that the MIZ was the receiving area for a considerable quantity of ice-melt derived, very low salinity water. It has generally been accepted that the approximate coincidence of the Bering ice edge, during its winter period of maximum southward extent, with the shelf break suggests an interaction' between ice edge-related and shelf break oceanographic processes. This interaction has not been, however, rigorously explored.

Temperature-salinity data were obtained along the Bering Sea MIZ in midwinter 1979 and reported on by Pease (1980). She noted that the ice edge was underlain by a two-layered water structure wherein a warmer, more saline lower layer underlay a colder, lower salinity upper layer. Similar water structures underlying the ice edge were noted using mid-late winter data from 1975 and 1976 (Niebauer et al., 1981). Finally, Newton and Andersen (1980) noted the same structure associated with the Bering ice edge in winter 1980 temperature-salinity data. These data, obtained prior to the present study, supported the concept of a water structure two-layered in temperature and salinity underlying the ice edge.

A theoretical argument for presence along the ice edge of wind-driven upwelling similar in nature to coastal upwelling was advanced by Clarke (1978). More recent work with numerical modeling techniques has suggested, however, that the off-ice winds which would lead to upwelling also lead to breakup of a discrete ice edge into bands, which in turn destroys the tendency toward upwelling (L. P. Røed, personal communication, 1981). At the present time, it therefore appears unlikely that wind-induced upwelling at the ice edge is a significant factor in the dynamics there. Hypotheses concerning the process have not yet, however, been fully developed.

Development of additional speculations or hypotheses concerning Bering Sea MIZ processes awaits further analysis of existing data or acquisition of new data. This report, by providing a summary analysis of newly obtained data, will further the development of knowledge on such processes.

2.1.3. Objectives

Overall objectives of the Bering Sea MIZ physical oceanographic program are to derive information on oceanographic processes associated with the MIZ which exert control over the fate and effects of OCS-related pollutants. Specific program objectives include:

- Definition of the large-scale (i.e. of order hundreds of km) fields of temperature and salinity (and derived density) and relating of these to regional oceanographic advective (transport) and diffusive (mixing) processes.
- Observation of small-scale (1-10 km) features (such as low salinity lenses and frontal structures) in the temperature and salinity distributions along the ice edge during winter and relating these where possible to regional oceanographic features, ice motion and distribution, and the wind field.
- Estimation, in conjunction with sea ice and meteorological data, of regional heat and salt balances.
- Estimation of the effects upon the water column of convective processes associated with local winds and with ice freezing.
- Estimation of the effects of both large- and small-scale water circulation features upon ice motion and distribution in the MIZ.

2.2. FIELD PROGRAM

2.2.1. Temperature and Salinity Observations

Two field activities involving temperature and salinity observations have been carried out under this program: an autumn (November 1980) observation program of regional temperature and salinity distributions combined with current meter mooring deployments, and a mid-winter (February-March 1981) program of detailed temperature and salinity observations along the ice edge. The mid-winter program was carried out simultaneously with intensive observations of meteorological and sea ice features. Recovery of the current meters which had been deployed in November 1980 was carried out in June 1981.

During the November 1980 program, 25 CTD casts were occupied in the portion of the Bering Sea normally occupied by the MIZ during winter (Figure 2-1). These CTD data were acquired from the NOAA vessel DISCOVERER using a Plessey Model 9040 CTD system with calibration and processing procedures carried out as per OCSEAP specifications. These November CTD data provide two transects extending across the shelf normal to the isobaths from about the shelf break to the 50-meter isobath and give a good representation of conditions over the central Bering Sea shelf including the MIZ. The observed distributions are discussed in the following section of this report. A listing of the autumn 1980 CTD stations is given in Table 2-1.

During the February-March 1981 field program, 64 CTD casts (2-65, Figure 2-2) were taken in the Bering Sea MIZ near the ice edge. (The initial single cast (1) was taken in the Gulf of Alaska near Unimak Pass for equipment calibration purposes.) These CTD data were taken from the NOAA vessel SURVEYOR using a Plessey Model 9040 CTD system; calibration casts were taken every third station. The geographical location of the winter field work within the overall study region

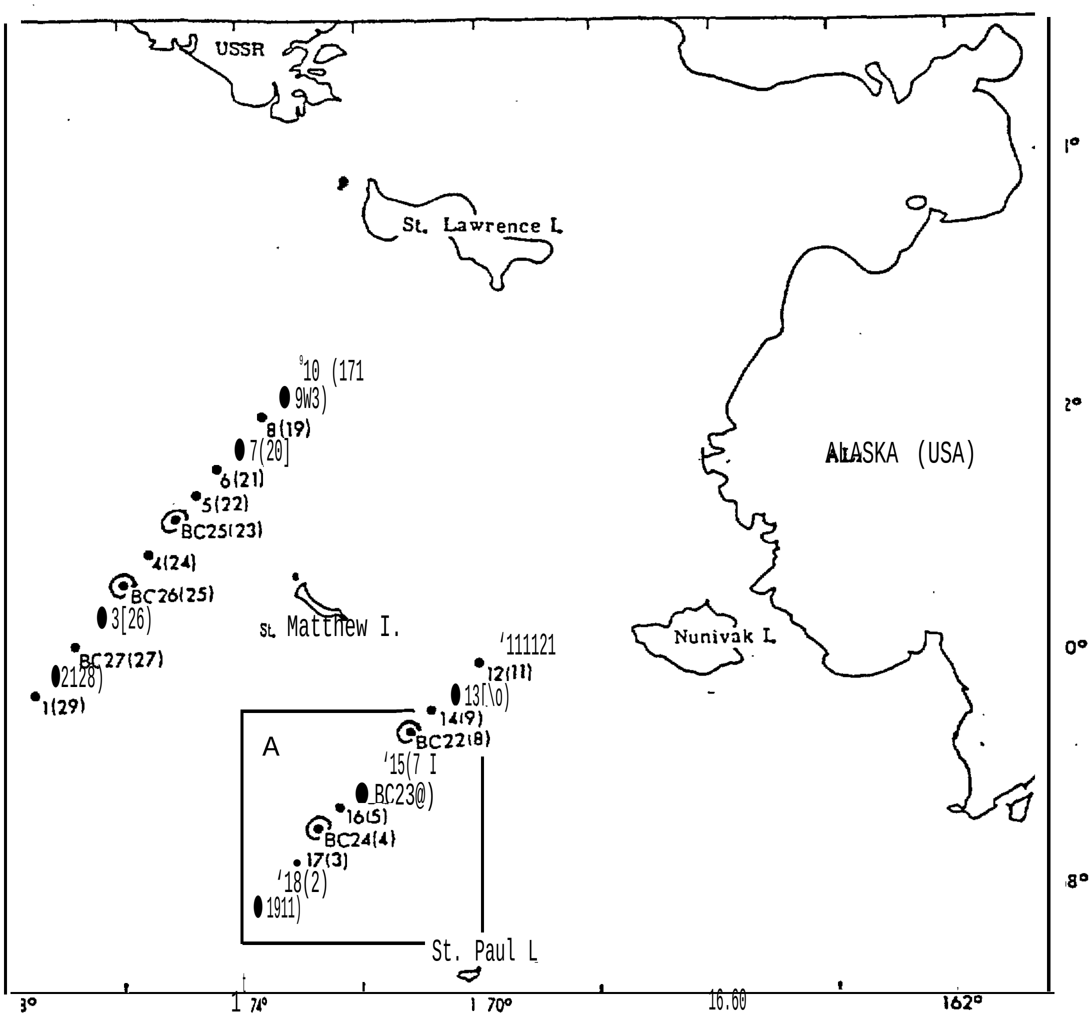

Figure 2-1. Geographical locations in the study region, showing positions of CTD stations occupied in November 1980 (.) and current meter moorings deployed from November 1980 - June 1981 (◉). First number at each station gives the station designation, while the second (parenthesized) number is the cast number. Geographical locations, depths and other information for stations are given in Table 2-1. The rectangular area "A" indicates the location of the February-March 198? winter field program which is shown in greater detail on Figure 2-2.

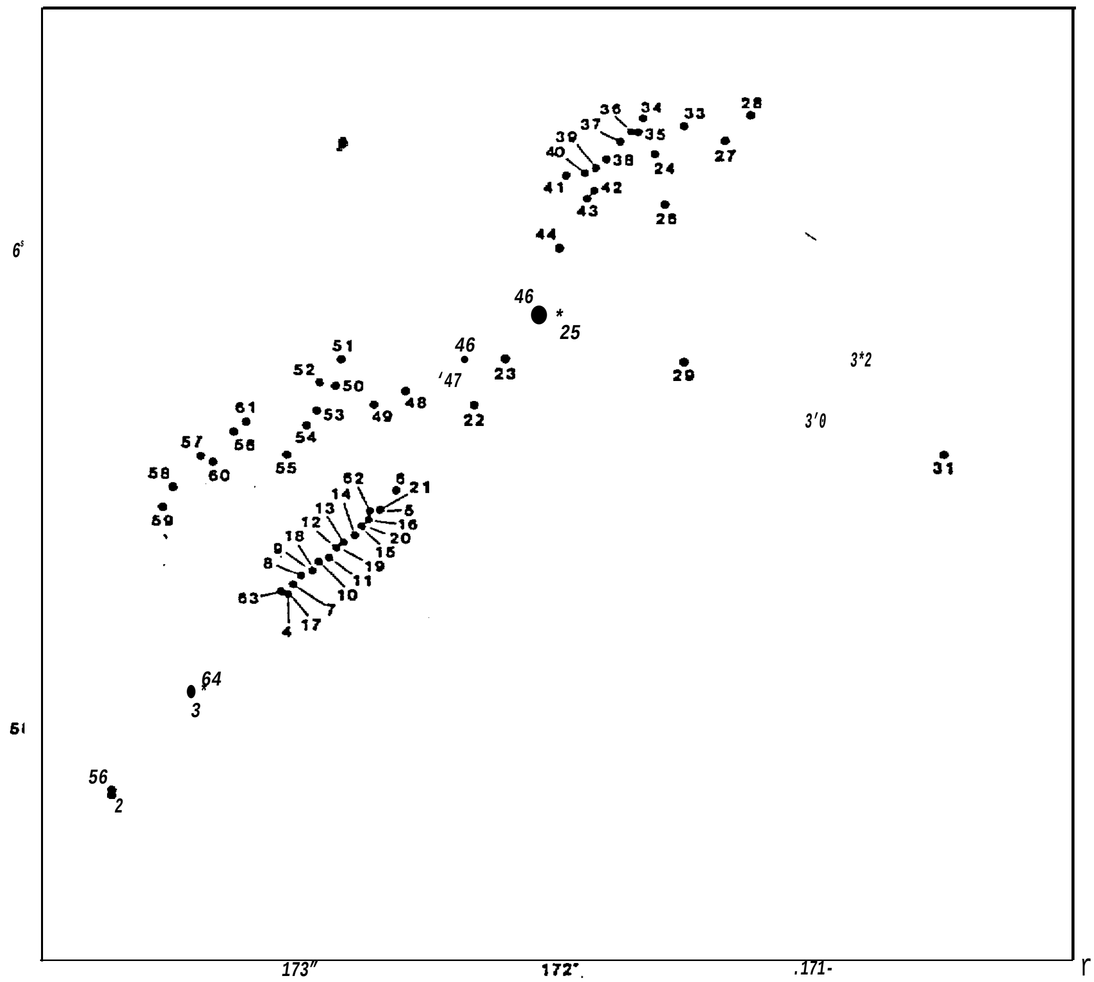

Figure 2-2. Locations of CTD stations occupied in the Bering Sea MIZ during February-March 1981. Numbers are cast numbers. Detailed information on each station is provided in Table 2-2. Geographical location of study region is indicated on Figure 2-1.

Table 2-1. Listing of CTD stations occupied in November 1980 in the central Bering Sea shelf region.

Consecutive Cast No.	Latitude (N)	Longitude (w)	Date (GMT)	JD (GMT)	Hour (GMT)	Bottom Depth (m)	Assigned Sta. No.
1	57-51.5	173-43.2	11-10	315	1440	137	19
2	58-03.8	173-21.7	11-10	315	1623	111	18
3	58-17.1	173-02.7	11-10	315	1759	110	17
4	58-28.1	172-41.1	11-10	315	1935	107 -	BC24
5	58-41.1	172-20.7	11-10	315	2159	97	16
6	58-51.8	171-59 .3	11-10	315	2331	91	BC23
7	59-05.7	171-35.8	11-11	316	0154	82	15
8	59-18.0	171-12.7	11-11	316	0327	76	BC22
9	59-31.1	170-50.8	11-11	316	0526	73	14
10	59-42.1	170-27.1	11-11	316	0658	65	13
11	59-55.9	170-02.9	11-11	316	0823	53	12
12	60-08.1	169-38.8	11-11.	316	.1013	48	11
17	62-21.0	172-50.1	11-13	318	0207	58	10
18	62-08.9	173-12.6	11-13	318	0334	60	9
19	61-57.0	173-37.0	11-13	318	0509	65	8
20	61-.$5.1	173-58.9	11-13	318	0635	73	7
21	61-32.1	174-20.7	11-13	318	0759	80	6
22	61-19.9	174-44.0	11-13	318	0931	86	5
23	61-08.0	175-05.7	11-13	318	1057	92	BC25
24	60-51.2	175-34.3	11-13	318	1316	106	4
25	60-34.1	176-01.5	11-13	318	1503	119	BC26
26	60-19.7	176-24.9	11-13	318	-1707	128	3
27	60-04. 3	176-49.8	11-13	318	1858	142	BC27
28	59-52.2	177-09.8	11-13	318	2103	135	2
29	59-39.2	177-30.3	11-13	318	2238	207	1

is indicated on Figure 2-1; the winter CTD station work included occupation of the outer (southern) eight stations on the southeastern transect shown on Figure 2-1, multiple occupation of a portion of this transect, and time series taken along the ice edge. A listing of the winter 1981 CTD stations is given in Table 2-2.

2.2.2. Current Observations*

Six current meter moorings were deployed in November 1980 at the locations indicated on Figure 2-1. Four of the six moorings were recovered in June 1981. Of those recovered, two malfunctioned so that only two current records were obtained. The current meter moorings are summarized in Table 2-3.

Current data were obtained using Aanderaa Model RCM-4 current meters deployed in a standard taut-wire mooring configuration such as described by Muench and Schumacher (1980). The current meters recorded at 30-minute intervals. Translation of the data from the current meter tapes onto 9-track tape was carried out at the Department of Oceanography, University of Washington. The data were filtered using a 35-hour running-average type filter and subsampled every 6 hours to provide de-tided data.

Table 2-2. Listing of CTD stations occupied in February-March 1981 in the central Bering Sea shelf region along the ice edge.

Consecutive Cast No.	Latitude (N)	Longitude (w)	Date (GMT)	JD (GMT)	Hour (GMT)	Bottom Depth (m)	Assigned Sta. No.
1	55-36.3	158-59.7	2-23	54	2333	114	
2	57-51.7	173-43.0	2-26	57	1315	136	19
3	58-03.8	173-24.7	2-26	57	1610	113	18
4	58-17.1	173-02.9	2-26	57	1921	112	17
5	58-27.9	172-41.1	2-26	57	2116	109	BC24
6	58-30.6	172-37.6	2-26	57	2255	108	
7	58-18.4	173-01.5	2-27	58	0642	111	
8	58-19.4	172-59.7	2-27	58	0724	111	
9	58-20.1	172-57.3	2-27	58	0811	111	
10	58-21.3	172-55.5	2-27	58	0857	112	
11	58-21.9	172-53.1	2-27	58	0937	111	
12	58-23.2	172-51.7	2-27	58	1023	112	
13	58-23.9	172-49.8	2-27	58	1054	110	
14	58-24.8	172-47.2	2-27	58	1135	110	
15	58-25.9	172-4$.9	2-27	58	1235	108	
16	58-26.8	172-43.8	2-27	58	1323	108	
17	58-17.2	173-02.6	3-01	60	0916	111	
18	58-20.2	172-56.6	3-01	60	1012	112	
19	58-23.1	172-50.9	3-01	60	1059	110	
20	58-26.1	172-45.1	3-01	60	1146	108	
21	58-28.2	172-41.1	3-01	60	1224	108	
22	58-41.1	172-19.6	3-01	60	1846	104	16
23	58-47.0	172-12.6	3-01	60	2200	101	BC23
24	59-11.9	171-37.9	3-02	61	2237	82	
25	58-52.0	171-59.2	3-03	62	0631	96	BC23
26	59-05.7	171-35.3	3-03	62	0827	83	
27	59-13.3	171-21.4	3-03	62	1048	81	
28	59-16.6	171-15.7	3-03	62	2037	78	BC22
29	58-46.5	171-30.8	3-04	63	0619	91	
30	58-40.6	171-00.7	3-04	63	0817	82	
31	58-34.9	170-30.7	3-04	63	1011	79	
32	58-48.3	170-49.9	3-04	63	1151	79	
33	59-15.5	171-31.2	3-04	63	1505	81	
34	59-16.4	171-40.7	3-05	64	0244	81	
35	59-14.7	171-41.8	3-05	64	0603	80	
36	59-14.7	171-43.1	3-05	64	0637	80	
37	59-13.4	171-45.4	3-05	64	0842	80	
38	59-11.4	171-49.0	3-05	64	1030	83	
39	59-10.3	171-51.4	3-05	64	1232	84	
40	59-09.6	171-54.0	3-05	64	1448	85	
41	59-09.3	171-58.1	3-05	64	1648	85	
42	59-07.5	171-51.9	3-05	64	2045	86	
43*	59-06.7	171-53.2	3-06	65	0049	79	
44*	59-00.4	171-59.8	3-06	65	0449	93	
45*	58-52.9	172-05.6	3-06	65	1244	97	
46	58-46.9	172-22.1	3-08	67	0037	102	
47	58-45.4	172-27.7	3-08	67	0442	104	
48	58-42.8	172-35.6	3-08	67	0915	106	

*Temperature record only, due to icing of conductivity cell.

Table. 2-2. (continued)

Consecutive Cast No.	Latitude (N)	Longitude (W)	Date (GMT)	JD (GMT)	Hour (GMT)	Bottom Depth (m)	Assigned Sta. No.
"49	58-41.3	172-43.0	3-08	67	1230	108 -	
.50	58-43.6 ,	172-51.8	3-08	67	'1654	112	
51	58-47.0	172-50.5	3-08	67	1913	110	
52	58-44.0	172-55.5	3-08	"67	2029	112	
53	58-40.6	172-56.1	3-08	67	2200	112	
54	58-38.7	172-58.6	3-08	67	2340	113	
55	58-35.1	17303.0	3-09	68	0100	114	
56	58-37.8	173-15.3	3-09	68	0438	119	
57	58-34.9	173-23.1	3-09	68	0845	122	
58	58-31.1	173-29.6	3-09	68	1232	123	
59	58-28.7	173-31.5	ABORTED - Surface values only				
60	58-34.1	173-20.3	3-10	69	1940	121	
61	58-39.1	173-12.8	3-10	69	2348	119	
62	58-28.1	172-43.7	3-11	70	0236	108	BC24 .
63	58-17.4	173-04.1	3-11	70	0513	112	17
64	58-04.3	173-22.2	3-n	70	0703	113	18
65	57-52.1	173-43.3	3-11	70	0851	137	19

Table 2-3. Listing of mooring deployments in the central Bering Seas shelf region during the over-winter 1980-1981 period.

Assigned Mooring ID	Latitude (N)	Longitude (W)	Deployment Date (GMT)	Deployment JD (GMT)	Deployment Hour (GMT)	Bottom Depth (m)	Meter Depth (m)	Meter Serial No.	Record Length (days)
BC22	59-10.4	171-11.4	11-11	316	0357	76	51	1813	207
BC23*	58-51.8	172-01.0	11-11	316	0007	95	52	3130	---
BC24**	58-28.3	172-42.4	11-10	315	2021	107	59	3128	110
BC25**	61-08.3	175-05.9	11-13	318	1128	95	52	3177	205
BC26	60-34.2	176-02.1	11-13	318	1531	119	52	3135	203
BC27*	60-04.6	176-49.6	11-13	318	1927	142	61	3131	---

*Not recovered.
**T and C records only due to malfunction.

2.3. TEMPERATURE, SALINITY AND DENSITY DISTRIBUTIONS

2.3.1. November 1980

Vertical distributions of temperature, salinity and density along the two CTD transects occupied in November 1980 are shown in Figures 2-3 to 2-8. The following features were common to both transects:

- The water column was two-layered vertically in temperature, salinity and density, with the interface between layers occurring at 50-60 m. The water was vertically well mixed above and below the interface. The interface between layers was 5-10 m shallower at the northwest than at the southeast transect, and was about 10-in thick.

- There was a relatively constant northeastward decrease in temperature, salinity and density in both the upper and lower layers in both transects. The ensuing horizontal gradients in either layer were approximately 0.01 °C/km, 0.003 °/oo/km and 0.003 sigma-t units/km, respectively.

- There was a tendency for slightly increased horizontal temperature and salinity gradients in both layers at the 80-90 m isobaths. However, this was not true for density due to the canceling effects exerted by the opposing temperature and salinity gradients on the density gradient.

- At about the 80-m isobath, there was a 50-km wide "bolus" of water which was about 1 °C colder than the surrounding water. This feature appeared on both transects, though the temperature of the bolus was about 2.5 ‘C lower on the northwest transect.

While the major feature of the comparison between the two transects was the similarity in distributions, overall water temperatures at the northwest transect were about 2 *C lower than to the southeast. Salinity and density were similar along the two transects. In the southeast section, there was some indication of salinity finestructure at the interface between layers (stations 3, 4 and 8, Figure 2-4); such finestructure was not evident anywhere in the transect to the northwest.

The tendency for water temperature to be lower along the northwest section is evident in the horizontal distributions of temperature in the upper and lower layers (Figures 2-9 and 2-10). The upper layer distribution shows maximum

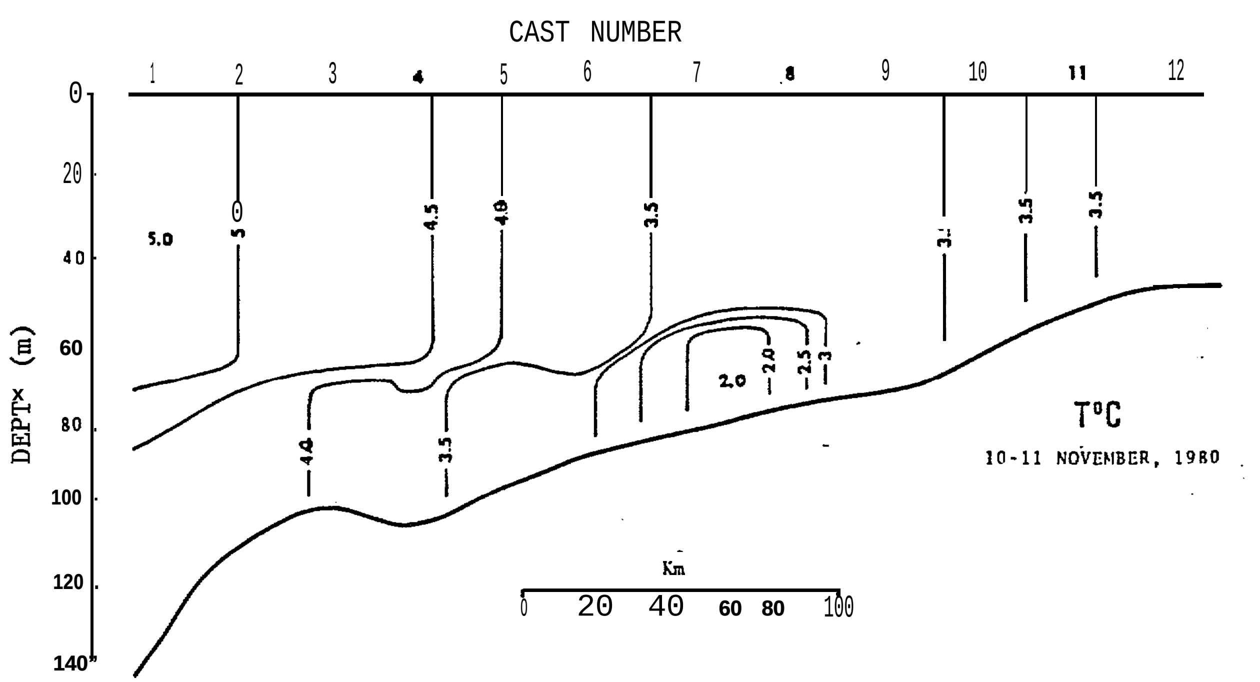

Figure 2-3. Vertical distribution of temperature across the central Bering Sea shelf in autumn 1980. Figure 2-1 shows locations of stations included in the transect. Numbers are cast numbers,

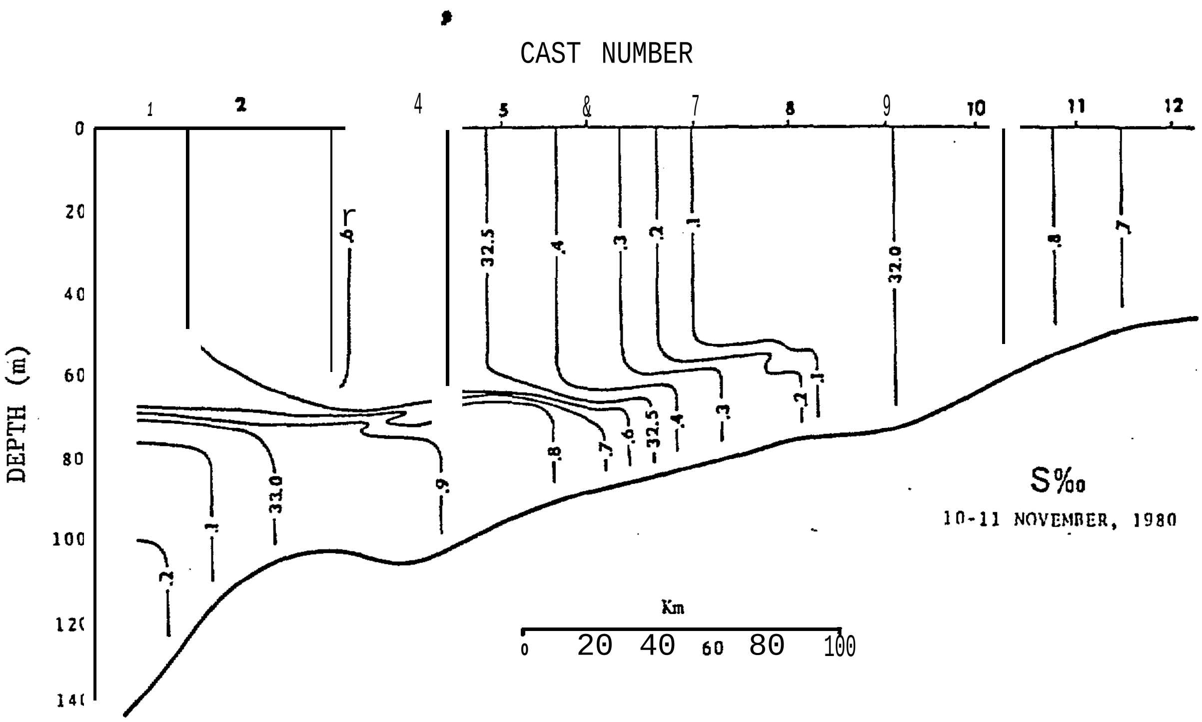

Figure 2-4. Vertical distribution of salinity; same transect as Figure 2-3.

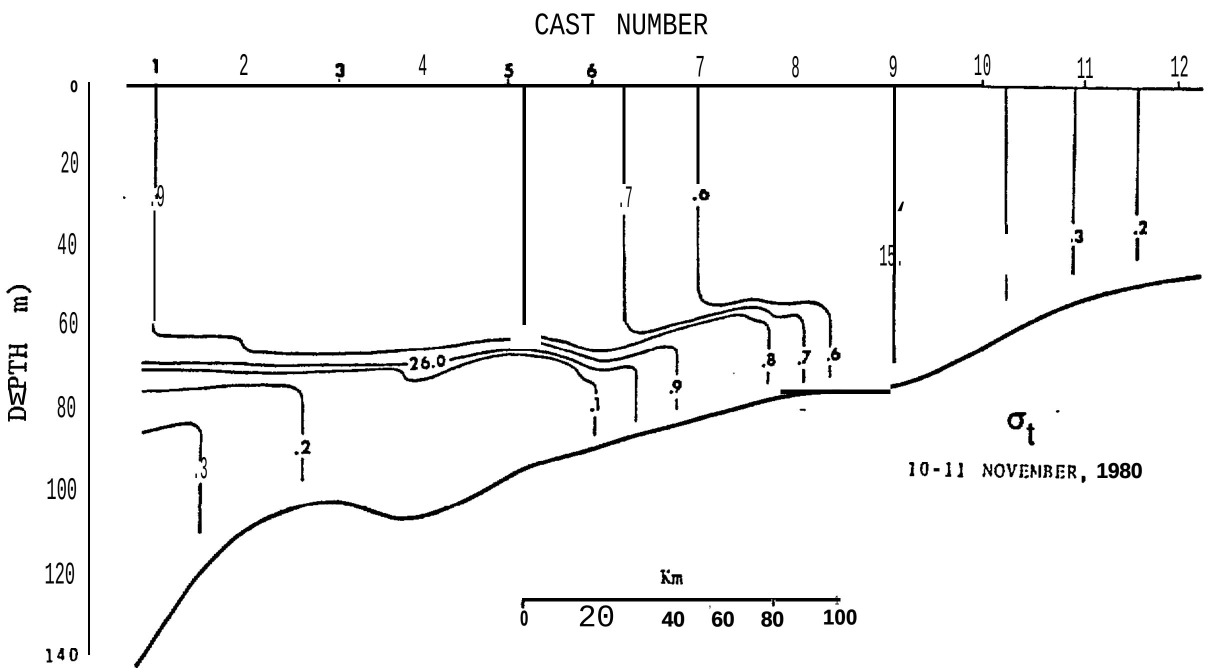

Figure 2-5. Vertical distribution of density (as sigma-t); same transect as Figure 2-3.

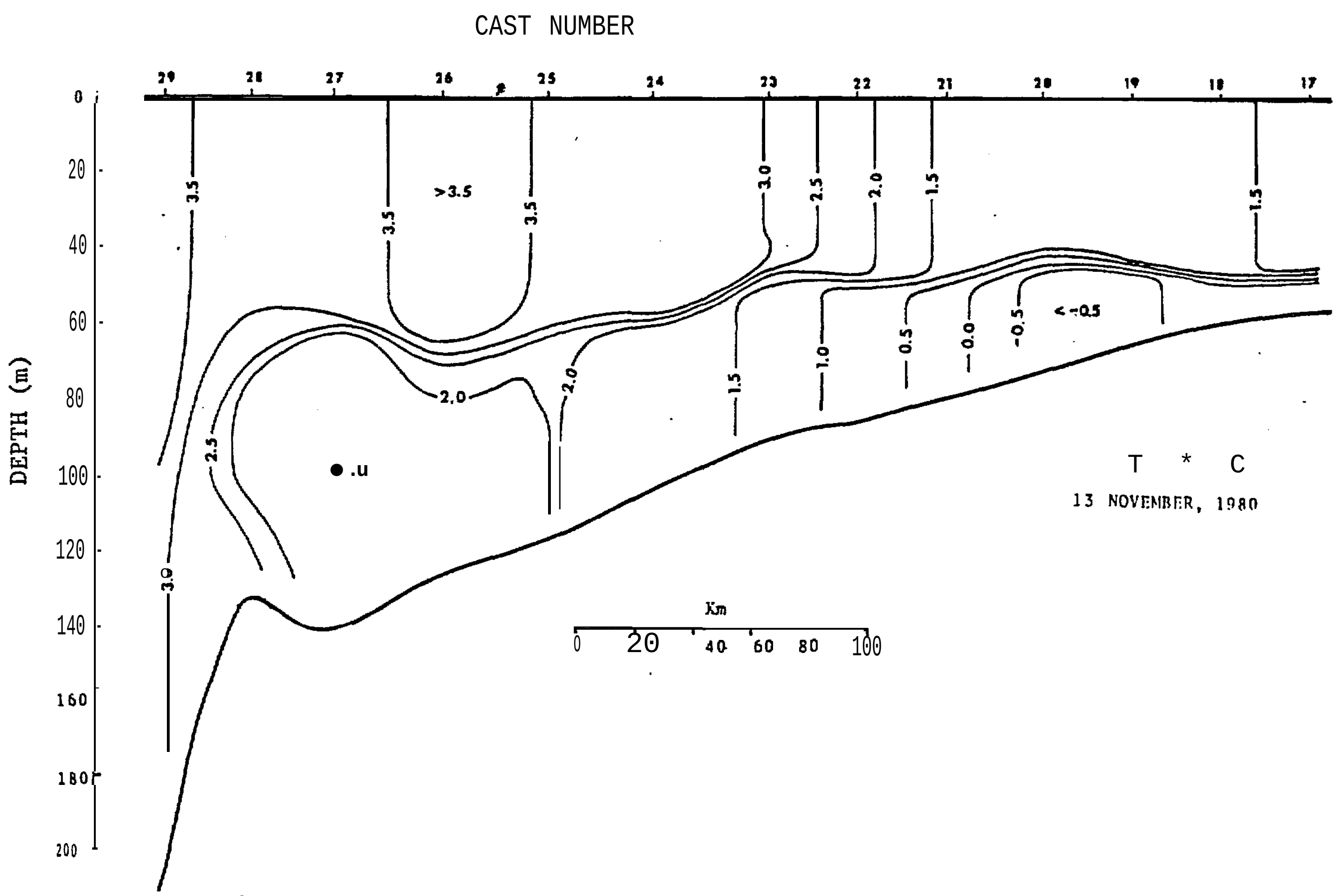

Figure 2-6. Vertical distribution of temperature across the central Bering Sea shelf in autumn 1980. Figure 2-1 shows locations of stations included in the transect. Numbers used are cast numbers.

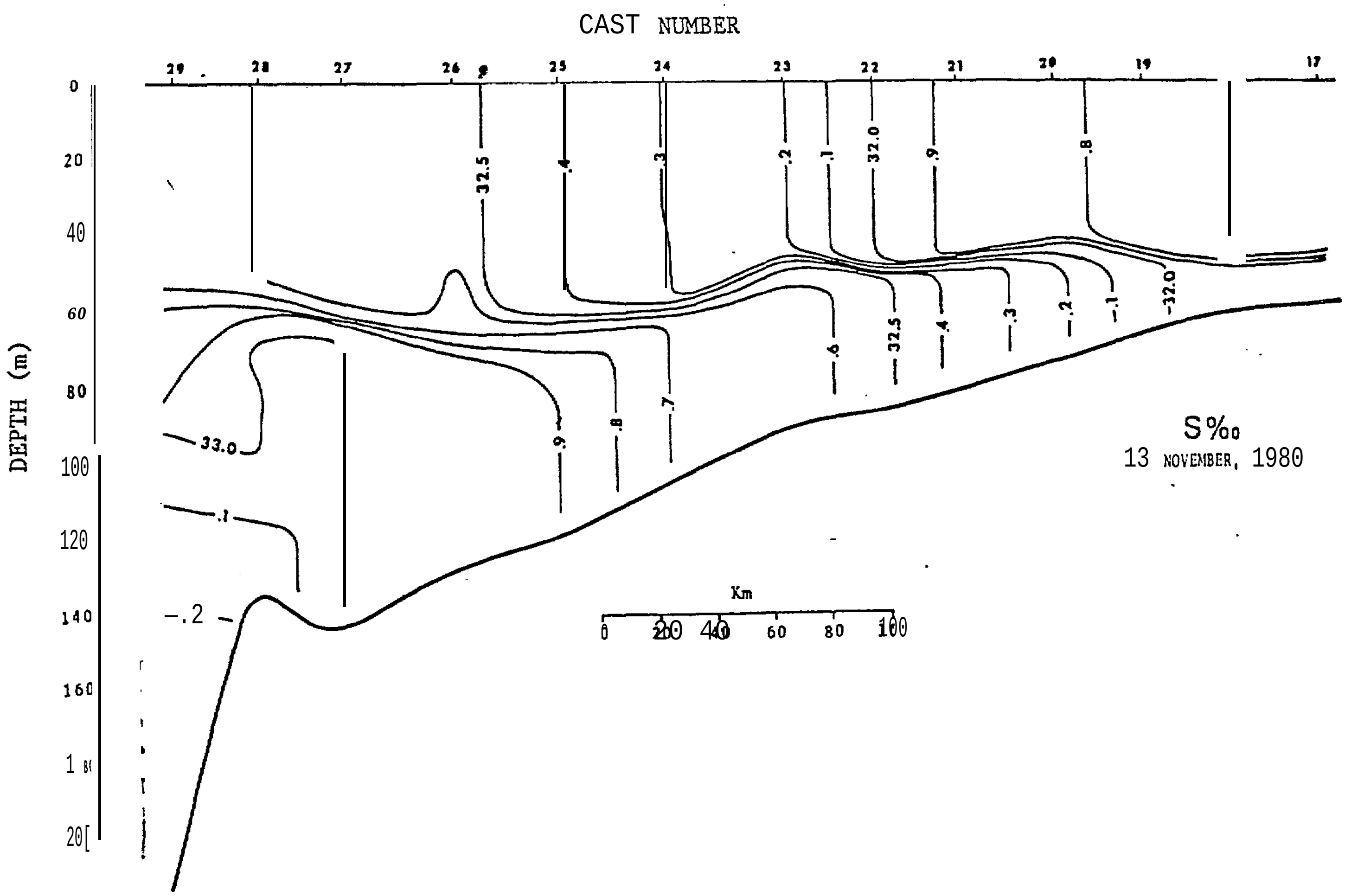

Figure 2-7. Vertical distribution of salinity; same transect as Figure 2-6.

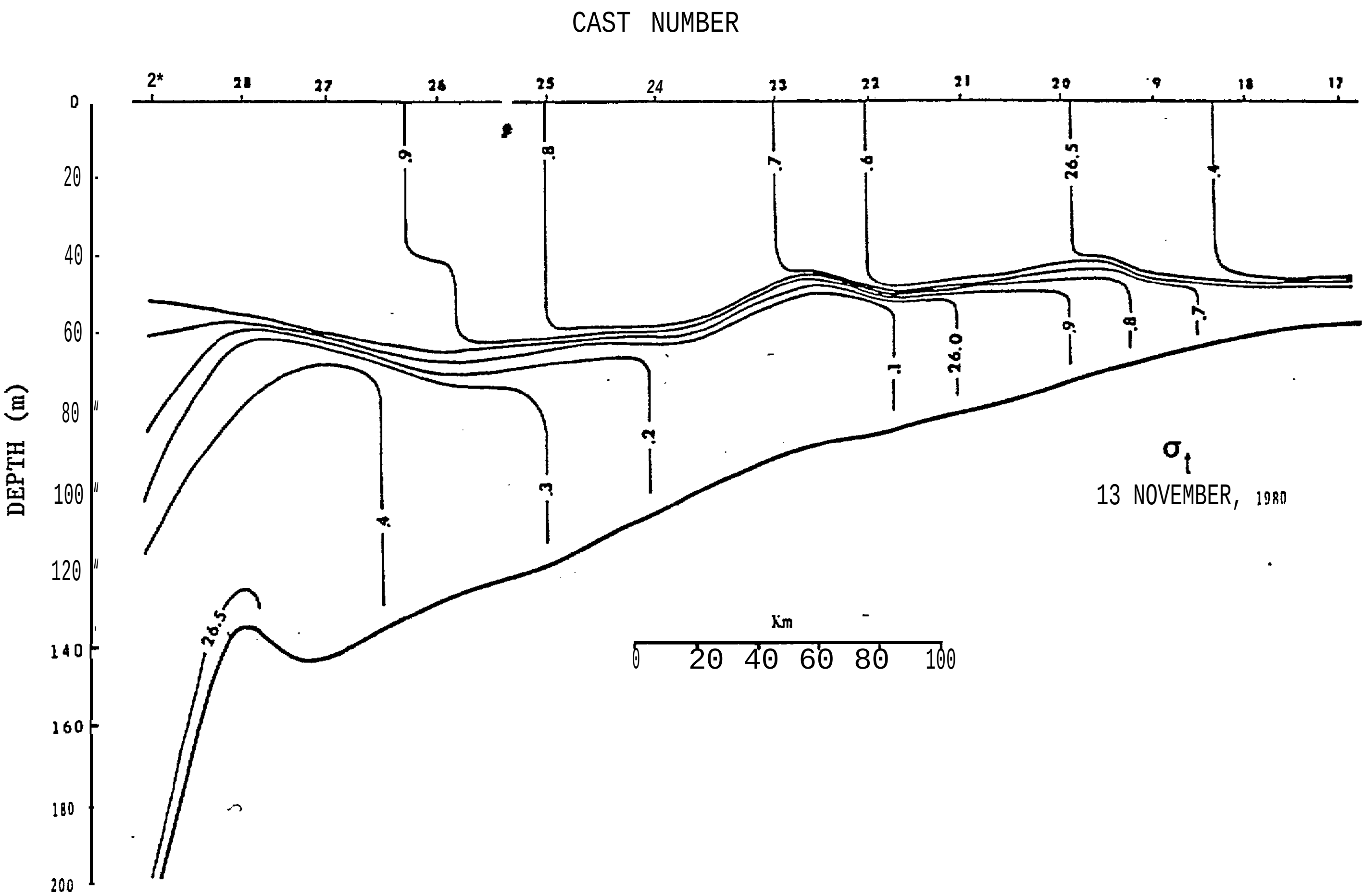

Figure 2-8. Vertical distribution of density (as sigma-t); same transect as Figure 2-6.

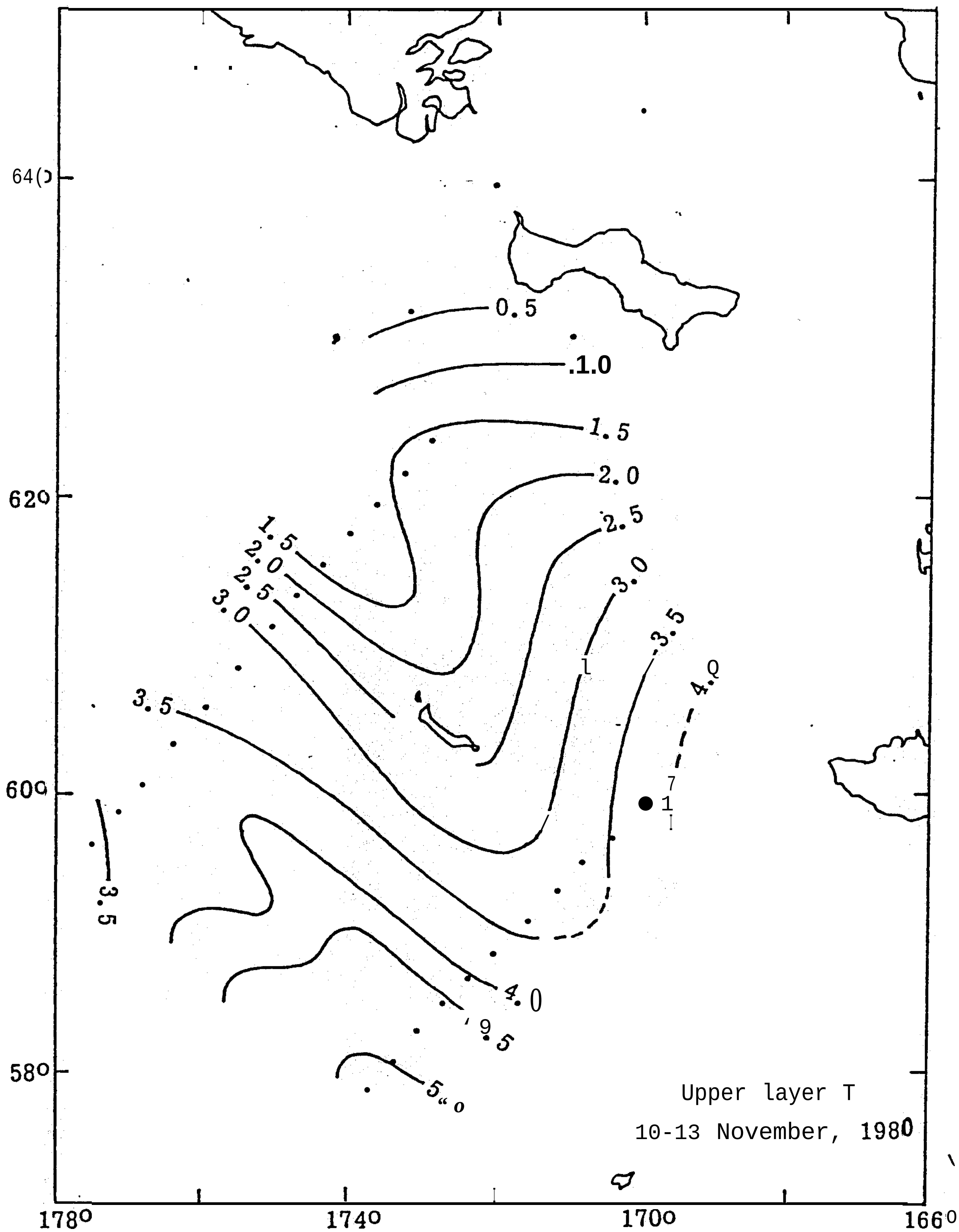

Figure 2-9. Horizontal distribution of temperature in the upper water layer during autumn, 1980.

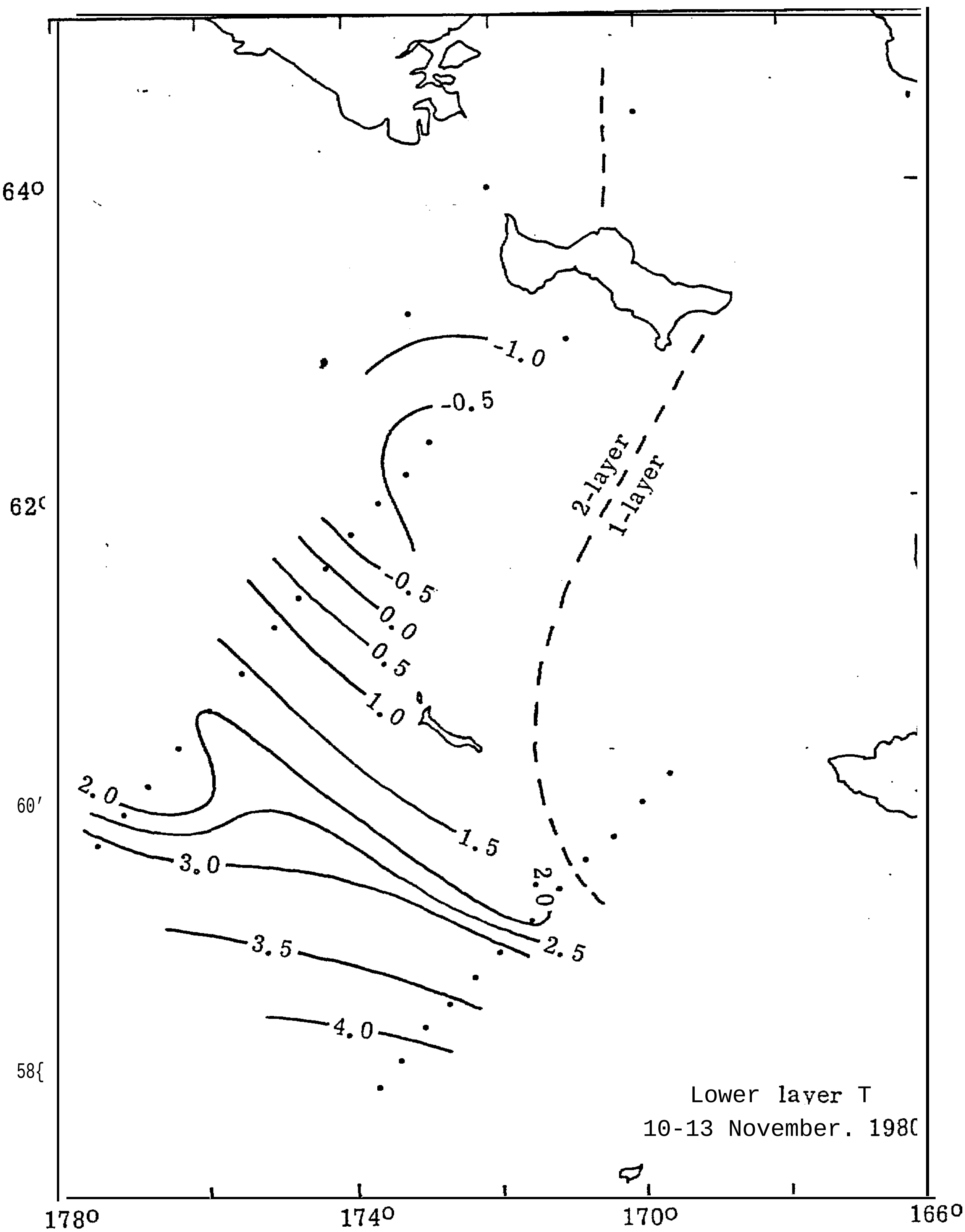

Figure 2-10. Horizontal distribution of temperature in the lower water layer during autumn 1980. Dashed line indicates boundary between water characterized by two-layered structure and vertically homogeneous water.

temperatures higher than 5 °C in the southern portion, with temperatures down to less than 0.5 "C in the north. The distribution shows a "tongue''-like, low-temperature (< 3.5 'C) feature extending toward the southeast from the northwest, with higher temperatures to the east along the Alaskan coast (4.0 'C) and to the southwest toward the shelf break (3.5-5.0 'C).

Lower layer temperatures (Figure 2-10) showed a similar pattern, except that temperatures were lower than in the upper layer. Minimum temperatures (< -1.0 "C) occurred to the north, with the highest temperatures (> 4.0 "C) to the south near the shelf break.

Upper-and lower-layer distributions of salinity (Figure 2-11) show maximum salinity in both layers near the shelf break and lowest values toward the north-east.

The cross-shelf horizontal density gradient evident in Figures 2-5 and 2-8 suggests that baroclinic northwestward flow may have-been present. Dynamic topographies of the surface relative to both 50 dbar and 100 dbar (Figure 2-12) confirm presence of a weak northwestward baroclinic flow tendency, in agreement with conventional wisdom concerning circulation on the Bering Sea shelf. The weak southeasterly counterflow at the southern end of the northwest transect is probably connected with a bolus of relatively cold (< 2.0 'C) water located in the lower layer (stations 25-28, Figure 2-6).

2.3.2. February-March 1981

Temperature-salinity data were acquired, during February-March 1981, along a transect which coincided with the southeastern of the two transects occupied

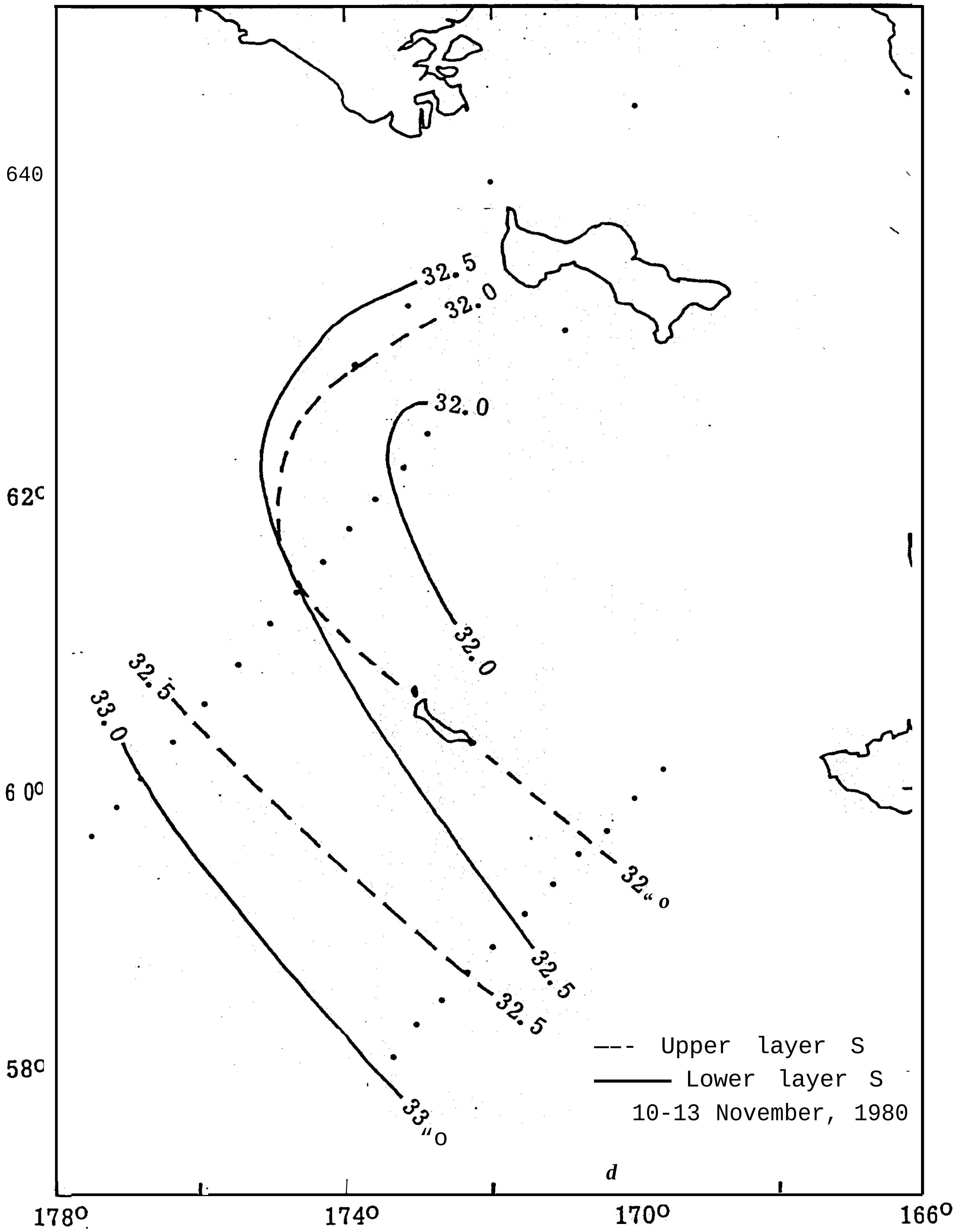

Figure 2-11. Horizontal distributions of salinity (°/oo) in both the upper and lower water layers during autumn 1980.

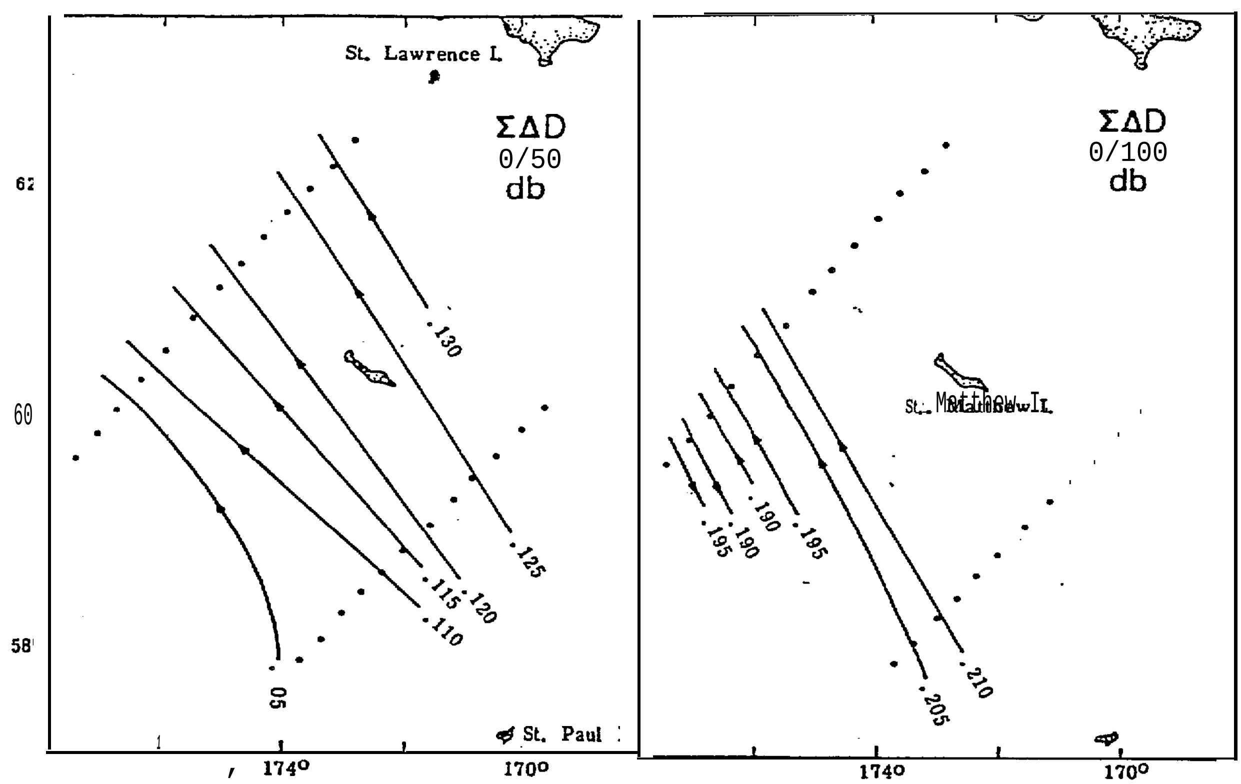

Figure 2-12. Dynamic topographies of the water surface relative to the 50 db (left) and 100 db (right) levels during autumn 1980. Arrowheads on contours indicate direction of baroclinic surface flow, relative to the reference levels, as implied by the dynamic topography. Contours are in dynamic meters, with contour interval of 0.5 dynamic centimeter,

in November 1980 (see Figure 2-1). The vertical distributions of temperature, salinity and density along the transect are shown on Figures 2-13 to 2-15. Stations 1-20 along this transect were south of the ice edge, while the remaining stations were occupied after the ice had been forced northward by strong south winds associated with a storm system. The temperature, salinity and density were near-homogeneous in the vertical in the southern part of the transect. In its northern portion, the water was vertically homogeneous, at or near the freezing point and had a salinity of about 31.9 ‰. A region about 80-km wide underlay the southern extreme location of the ice edge and was characterized by two-layered water structure. The lower layer was warmer (> 1.0 °C) and more saline (32.5-32.7 ‰) than the upper layer (< 0.5 °C and 32.1-32.6 ‰). The lower layer was continuous in temperature and salinity properties with water to the south; that of the upper layer with water to the north.

Two separate occupations were obtained along part of the transect shown in Figures 2-13 to 2-15. These separate occupations documented variation in the water column during passage over the region of a severe storm having south winds which forced the ice edge northward. Temperature is well correlated with salinity and density (Figures 2-13 to 2-15) and may be used as a tracer of water properties. This is done in Figure 2-16, which shows the water structure before and after passage of the storm along the southern portion of the two-layered structure which underlay the ice edge. Prior to the storm, on 27 February, the lower layer was well-mixed and the upper layer was stratified. After the storm, on 1 March, both layers were well-mixed and the upper layer had been considerably deepened at the southern extreme of the two-layered structure. Despite the

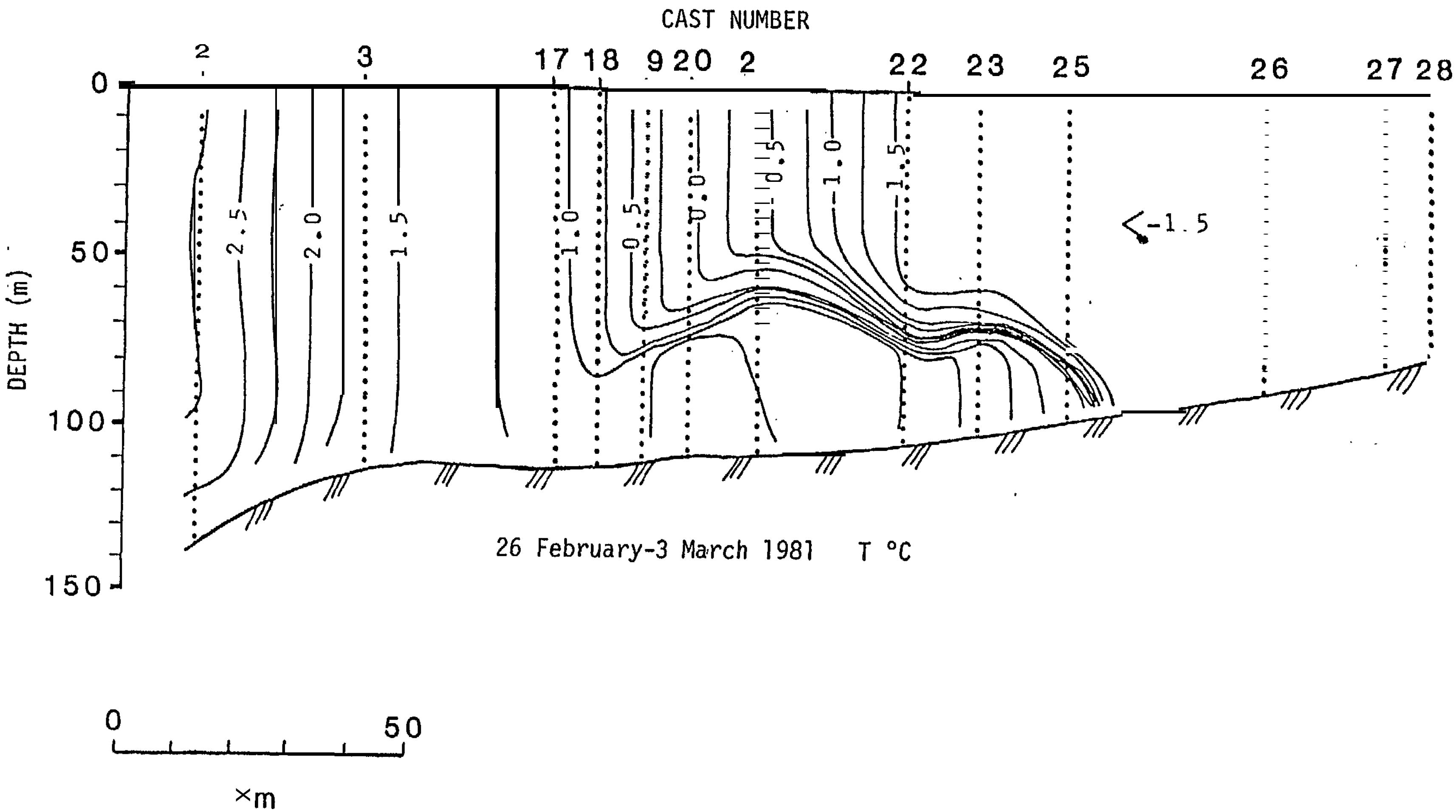

Figure 2-13. Vertical distribution of temperature across the central Bering Sea shelf in mid-winter 198 . Figure 2-2 shows locations of stations wh ch are included in this transect. Numbers given are cast numbers.

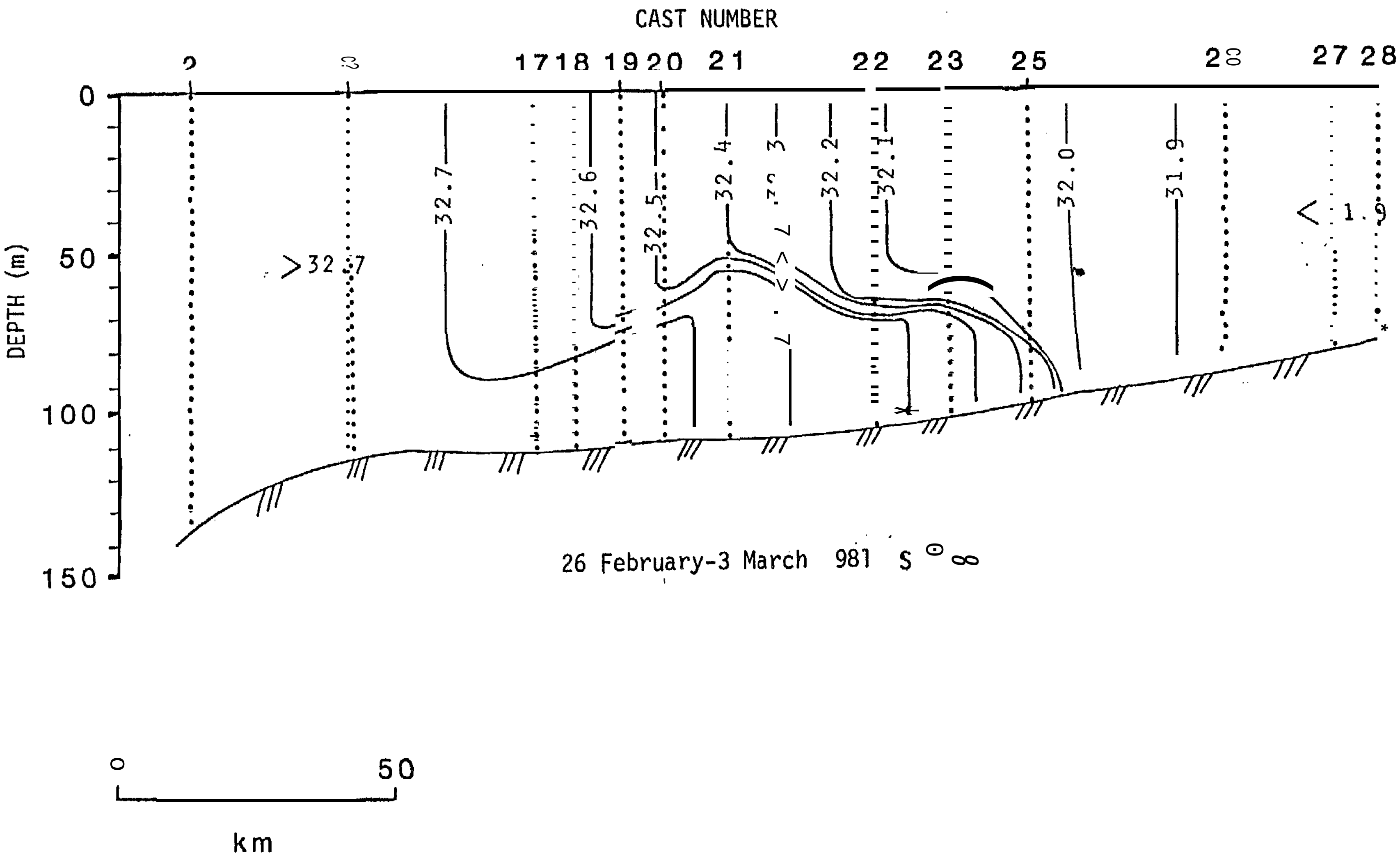

Figure 2-'4. Vertical distribut·on of salinity same transect as Figure 2-13.

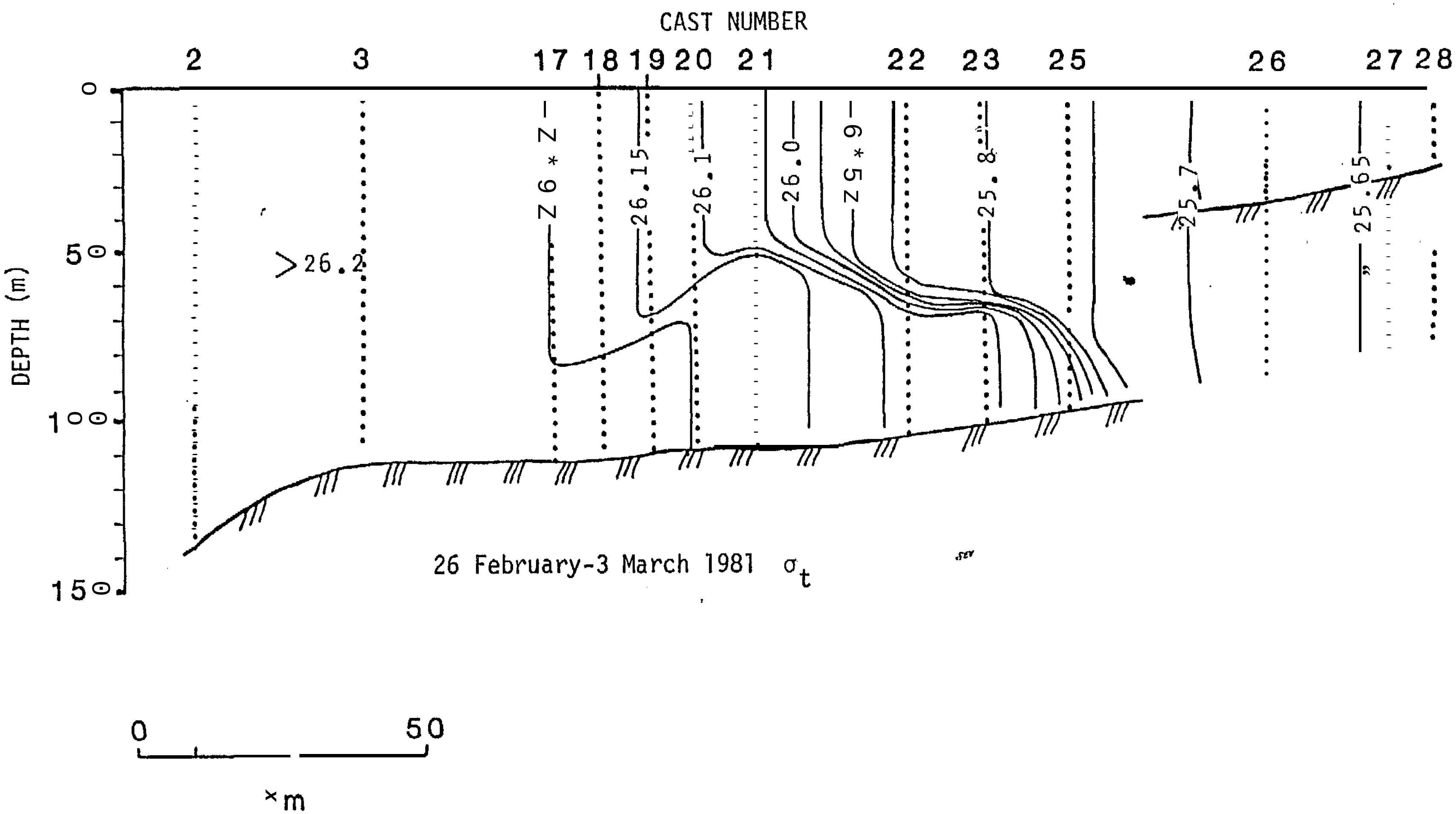

Figure 2-15. Vertical distribution of density as σ-t, same transect as Figure 2-13.

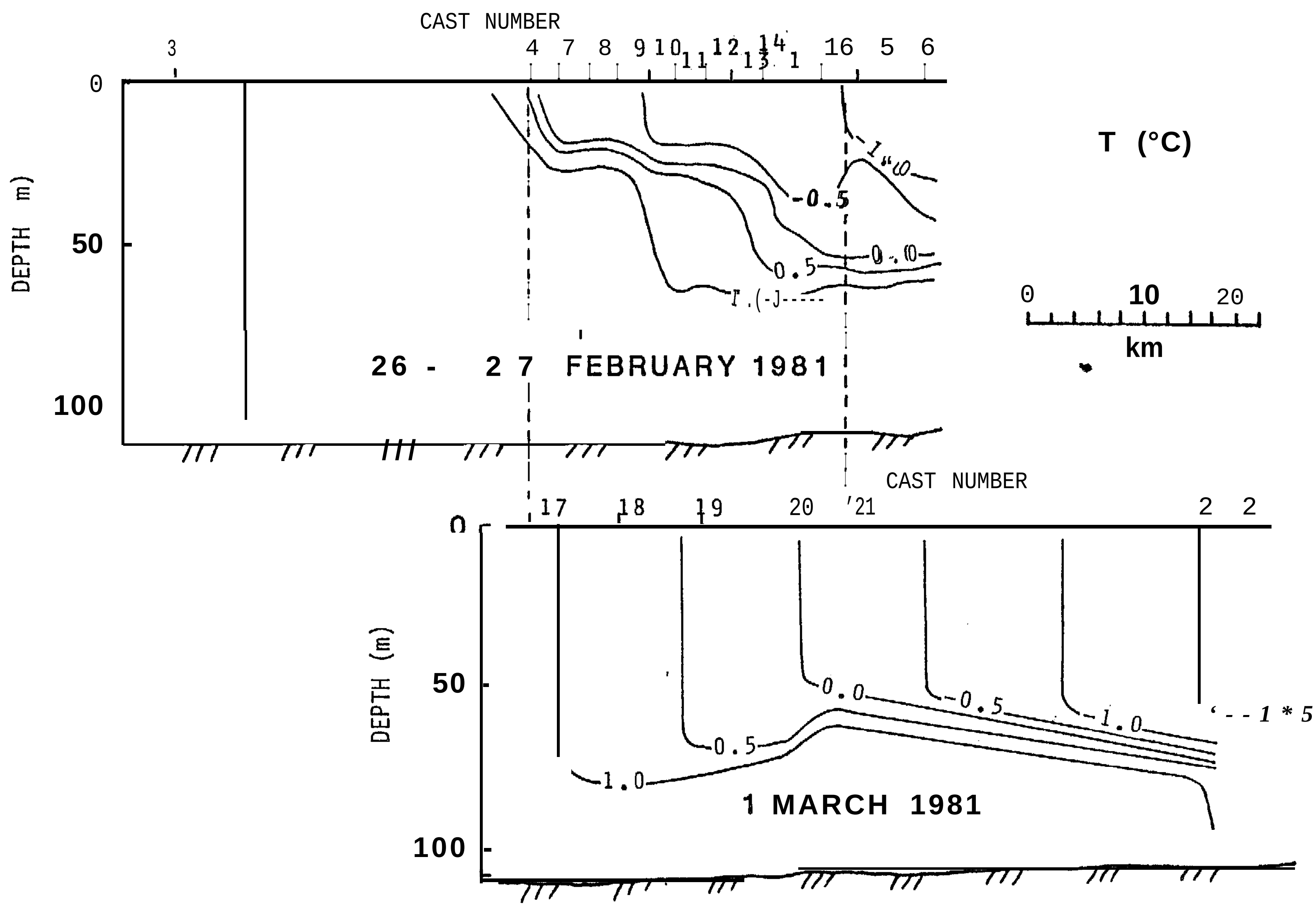

Figure 2-16. Vertical distribution of temperature across the central Bering Sea shelf, approximately beneath the ice edge, prior to (upper) and following (lower) a strong, southerly wind event in mid-winter 1981. Figure 2-2 shows locations of stations which are included in these two transects. Numbers given are cast numbers.

obvious change in structure, however, the locations where isotherms intersected the surface at the south edge (the 1.0 "C isotherm) did not shift more than about 20 km northward during the period when the ice edge itself was forced about 100 km to the north. Moreover, the vertical heat content of the water column did not change significantly during the storm event. It is concluded that the change in structure between 27 February and 1 March was due to wind mixing of the upper layer and its subsequent deepening due to erosion of the pycnocline.

The transitions between vertically homogeneous water (to the north) and near-homogeneous water (to the south) and the two-layered structure are compared in Figure 2-17 with ice edge locations. This figure shows the spatial relation of the two-layered structure to the ice edge at the various ice edge locations observed from 26 February-n March 1981.

A final example of the observed short-term variability in vertical water structure is given in Figure 2-18. This shows vertical density profiles at a station south of the ice "edge" on three separate occupations. The 20 February structure preceded the storm event, while the 1 March profile directly followed it and shows-wind-mixing of the upper layer. The 11 March profile shows the upper layer returning toward its original" (i.e. as observed on 26 February) stratified state. The change in density in the lower layer was probably advective in origin, which suggests that some portion of the upper layer variability was, also, advective rather than due entirely to wind-mixing. Presence to the southwest of denser lower-layer water suggests that a northward current pulse might have led to such an increase in density. Data are, however, inadequate to test this speculation.

Finally, as for the November density structure, that observed in February-March suggests a baroclinic flow to the northwest. This is confirmed by the

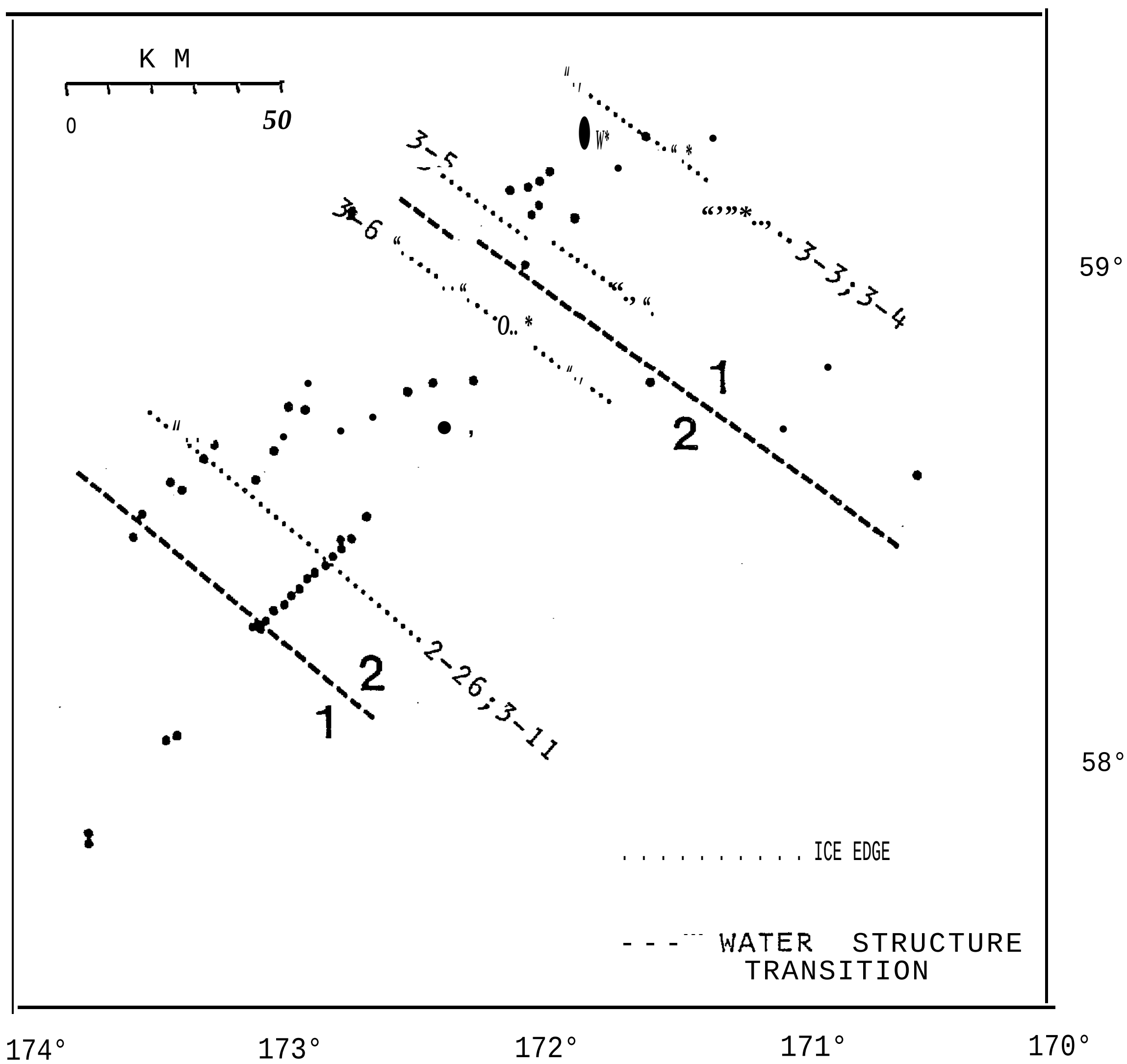

Figure 2-17. Horizontal plan view indicating schematically the fluctuations in ice edge location (dotted lines, with numbers Indicating month-day of location), and position of two-layered water structure which was associated with the ice edge region (between two heavy, dashed lines) observed during mid-winter, 1981. Two-layered structure is indicated by the numeral "2", whereas homogeneous or nearly homogeneous water is indicated by "l",

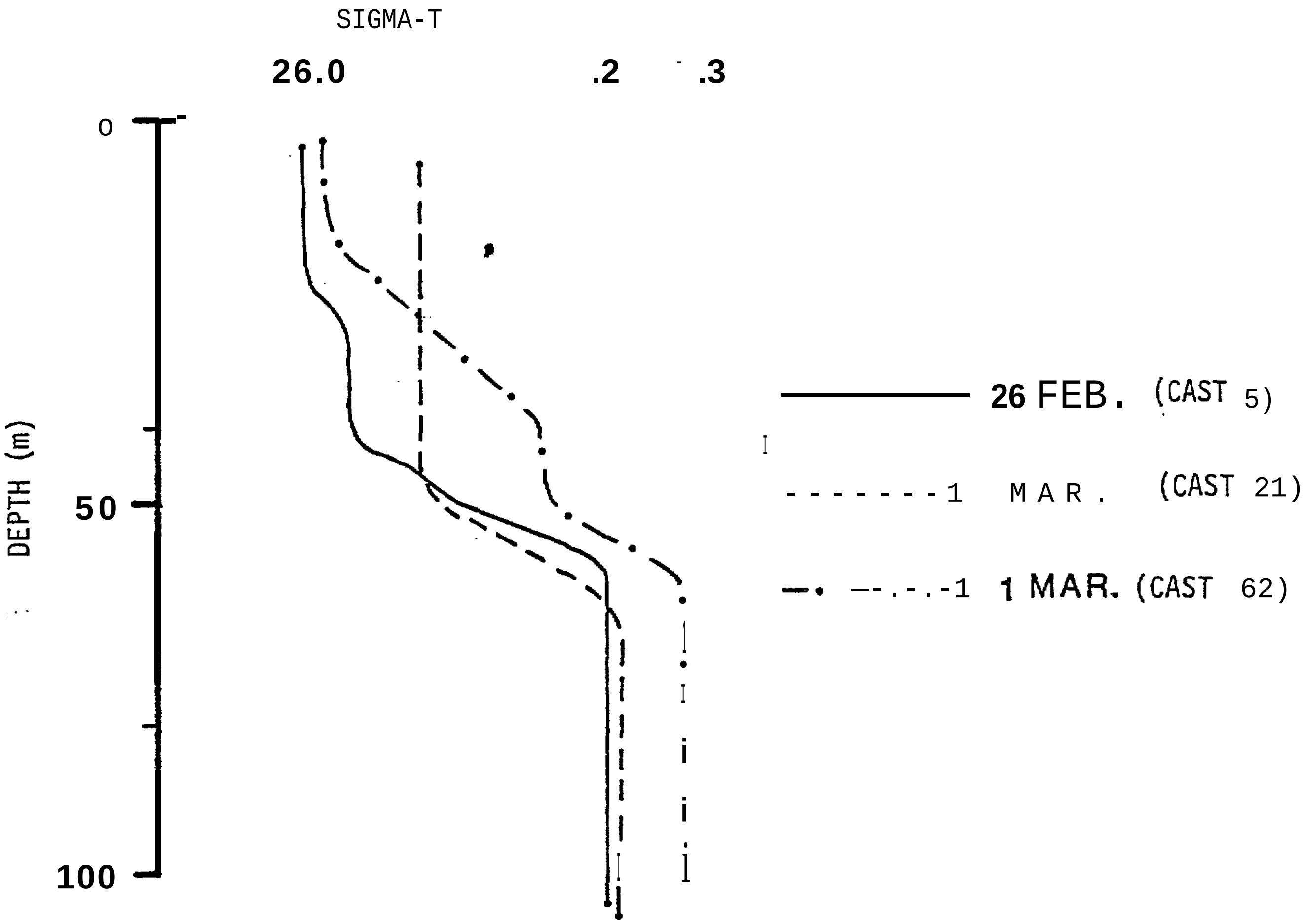

Figure 2-18. Vertical density profile (as sigma-t) on the central Bering Sea shelf during mid-winter preceding (26 February), directly following (1 March) and following by several days (11 March) a strong, southerly wind event, Figure 2-2 shows locations of stations from which these profiles were derived. Numbers given are cast numbers.

dynamic topography of the surface relative to 75 db (Figure 2-19). The computed surface current speed, assuming 75 db as a level of no motion, was about 7 cm/sec toward the northwest and was 'confined to the area bounded by the two-layered structure. This baroclinic flow will be discussed at greater length in Sections 2.4 and 2.5 below.

2.3.3. Temperature-Salinity Characteristics

The central Bering Sea shelf region was characterized, both in autumn 1980 and mid-winter 1981, by a vertical structure" which was two-layered in temperature and salinity. In autumn, this structure covered the shelf from the shelf break to north of the 50-m bottom isobath. In mid-winter, this layered structure was confined to a "band" approximately 100 km in width which underlay the location of the ice edge.

The observed temperature and salinity characteristics can be compared with those elsewhere in the Bering Sea region by plotting-them superimposed on the diagram constructed by Kinder and Schumacher (1981) to illustrate Bering Sea temperature-salinity relationships (Figure 2-20). It is readily apparent that observed salinities were, for both seasons during which data were obtained, more characteristic of Alaska Stream/Bering Sea Water than Bering Shelf Water. Temperatures were lower than those typical of Alaska Stream/Bering Water, but our data were obtained later in the season than that analyzed by Kinder and Schumacher and so would have been subject to greater cooling. The February-March data were similar in salinity to the November 1980 data, but minimum observed temperatures were lower (-1.7 °C) as would be expected for winter as compared to autumn data.

In summary, temperature and salinity data obtained during autumn 1980 and mid-winter 1981 suggest that water on the central Bering Sea shelf has characteristics

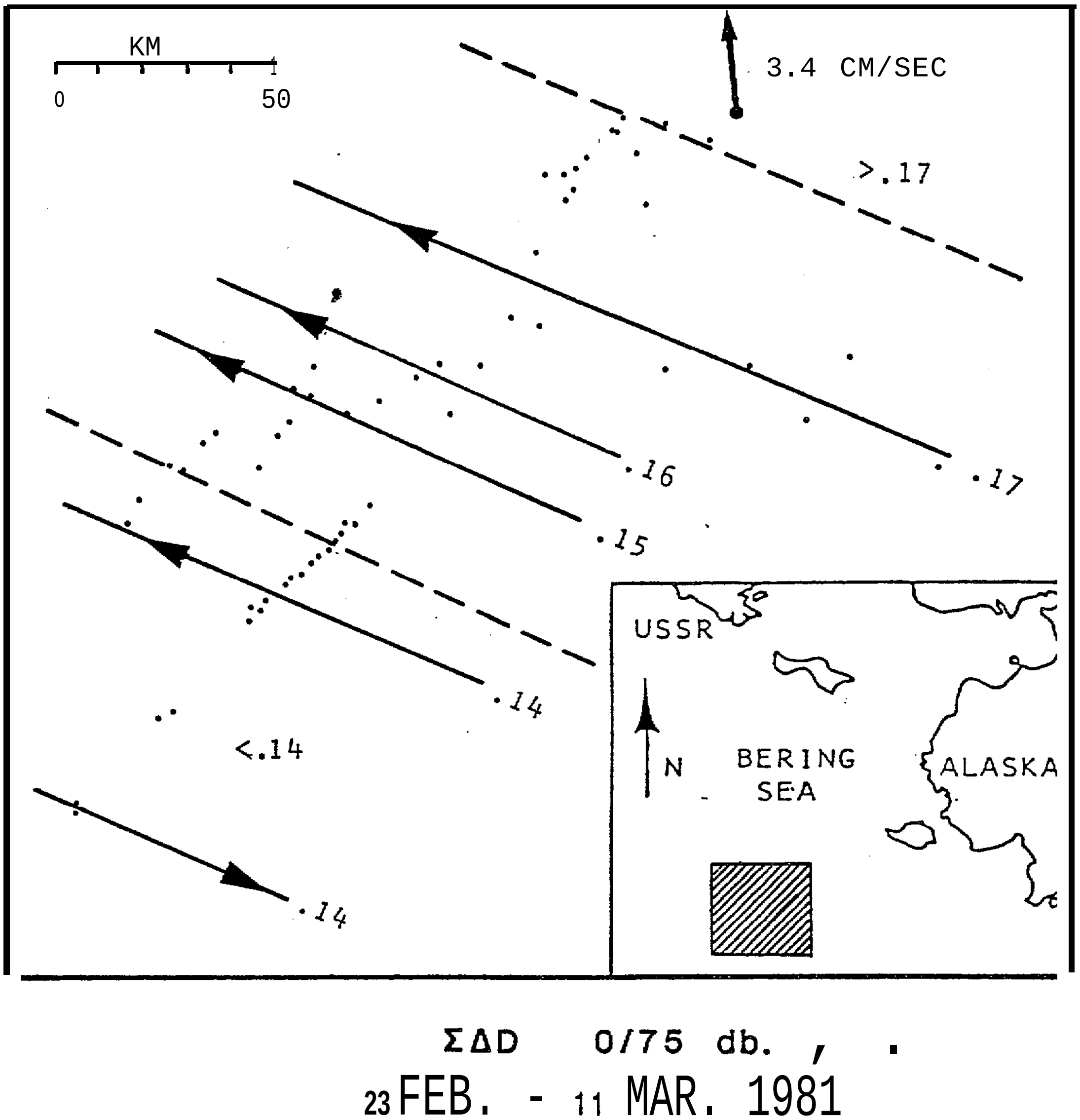

Figure 2-19. Dynamic topography of the water surface relative to the 75 db level during mid-winter 1981. Arrowheads on contours indicate direction of baroclinic surface flow, relative to the reference level, as implied by the dynamic topography. Contours are in dynamic meters, with contour interval of 1 dynamic centimeter. Arrow indicates vector-averaged February-March flow at 50 m, as observed from mooring BC22. Inset map shows general location on the central Bering Sea shelf region (shaded rectangle).

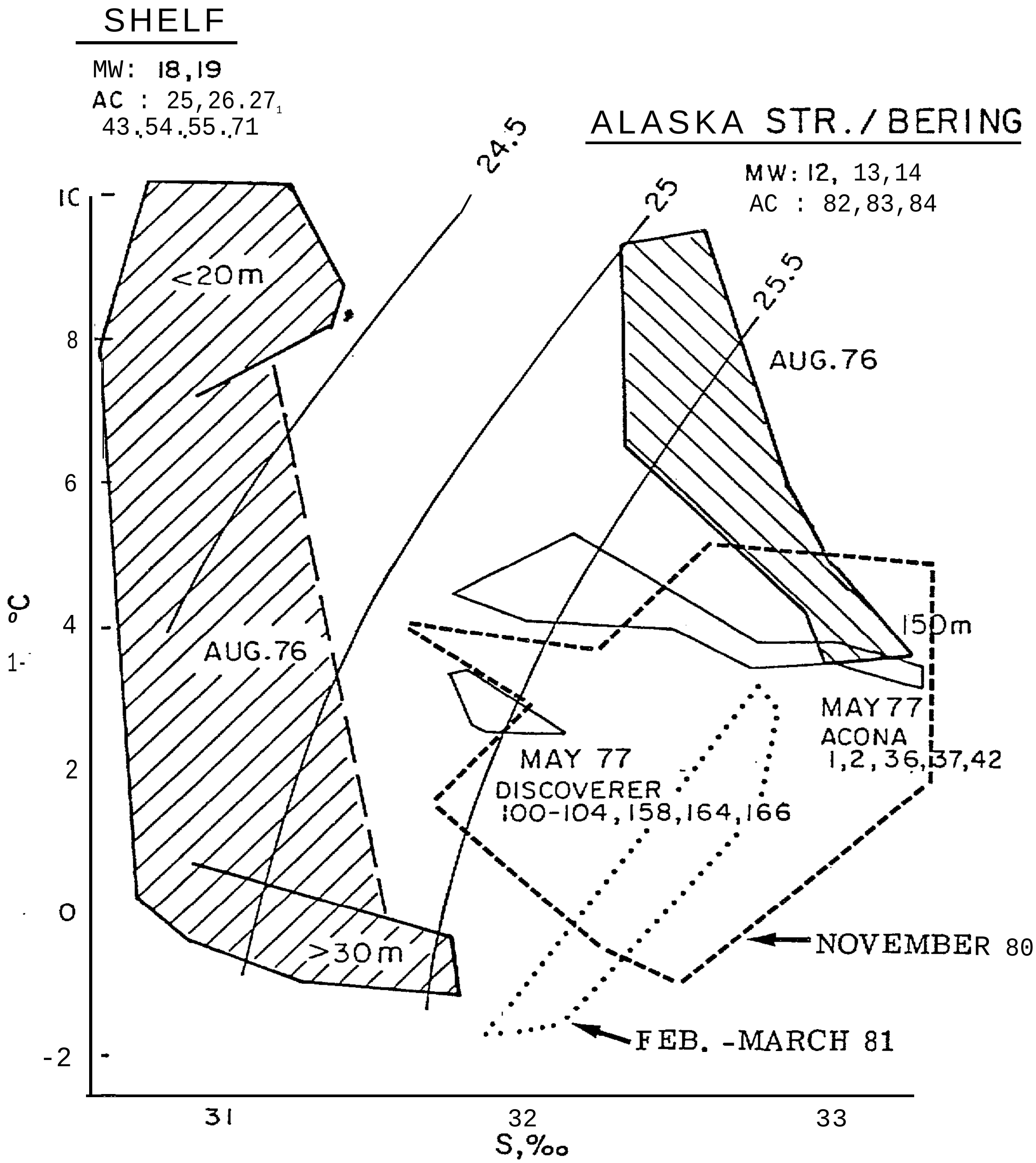

Figure 2-20. Comparison between temperature-salinity characteristics observed in autumn 1980 and mid-winter 1981 on the central Bering Sea shelf, and those compiled for the southeastern Bering Sea shelf by Kinder and Schumacher (1981).

more typical of Alaska Stream/Bering Sea Water than of that classified by Kinder and Schumacher (1981) as Shelf Water farther to the southeast. This difference was due to a large (1-1.5 $^{o}/_{oo}$) salinity difference between waters on the southeast and on the central Bering Sea shelf. Speculation concerning this observation is presented in Section 2.5 below.

2.4. CURRENT OBSERVATIONS

Two current records, each more than 200 days in length, were obtained from 50-m depths on the central Bering Sea shelf between November 1980 and June 1981. Geographical locations of these current records are shown on Figure 2-1; other pertinent information is listed in Table 2-3.

Both of the overwinter 1980-81 current records supported the concept of a mean, northwesterly flow along the central Bering Sea shelf. The vector-averaged current for the entire record at mooring BC22 was 2.3 cm/see, directed toward 340 'T. That from mooring BC26 was 3.3 cm/see, directed toward 347 'T. These directions closely approximated the local trend of the isobaths. Speeds were somewhat higher than the approximately 1 cm/sec means given by Kinder and Schumacher (1981b) for the mid-shelf regime farther southeast.

The high-frequency components of flow at both moorings BC22 and BC26 were heavily dominated by tidal currents which were mixed, predominantly-diurnal. These show clearly in the time-series segment of raw current data presented in Figures 2-21 (for BC22) and 2-22 (for BC26). Visual inspection of these time series reveals tidal currents varying between about 20 to 40 cm/sec at BC22 and 10 to 30 cm/sec at BC26. This decrease in tidal current speeds between BC22 and BC26 is in qualitative agreement with Pearson et al. (1981), who indicate that diurnal tidal currents decrease in magnitude toward the western Bering Sea shelf.

While the tidal currents were the highest speed components, lower frequency (1 to 10 day period) fluctuations in speed and direction were evident throughout the observation period. The tidal signal has been removed from the current vectors in Figure 2-23 in order to illustrate these fluctuations. Time scales were of order 7 to 10 days, and reversals to southeastward flow occurred and were more

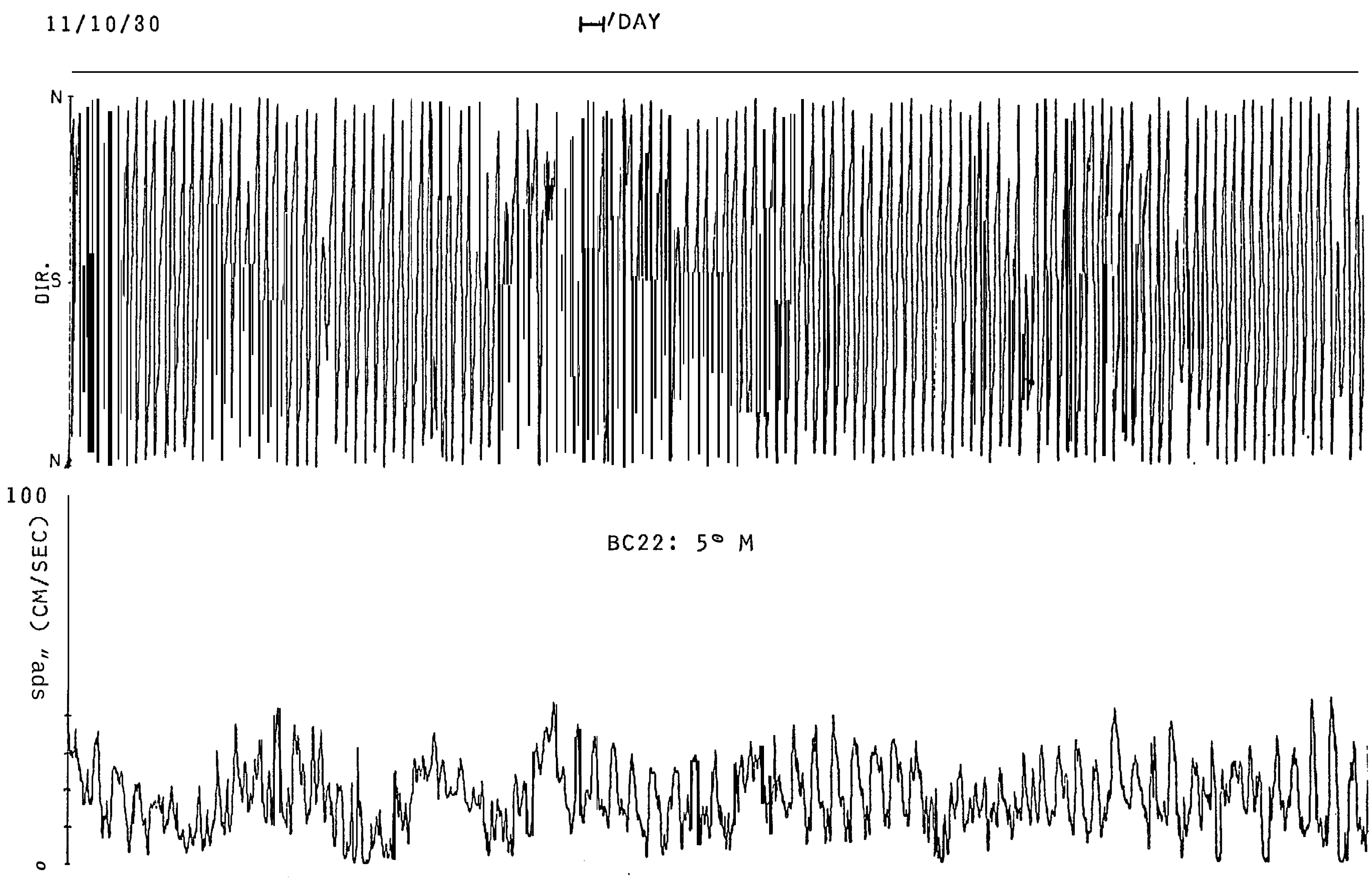

Figure 2-21. 70-day segment of raw current speed (lower) and direction (upper) as observed at 50-m depth at mooring BC22. Start date for this plot is 10 November 1980 and each time mark represents 1 day.

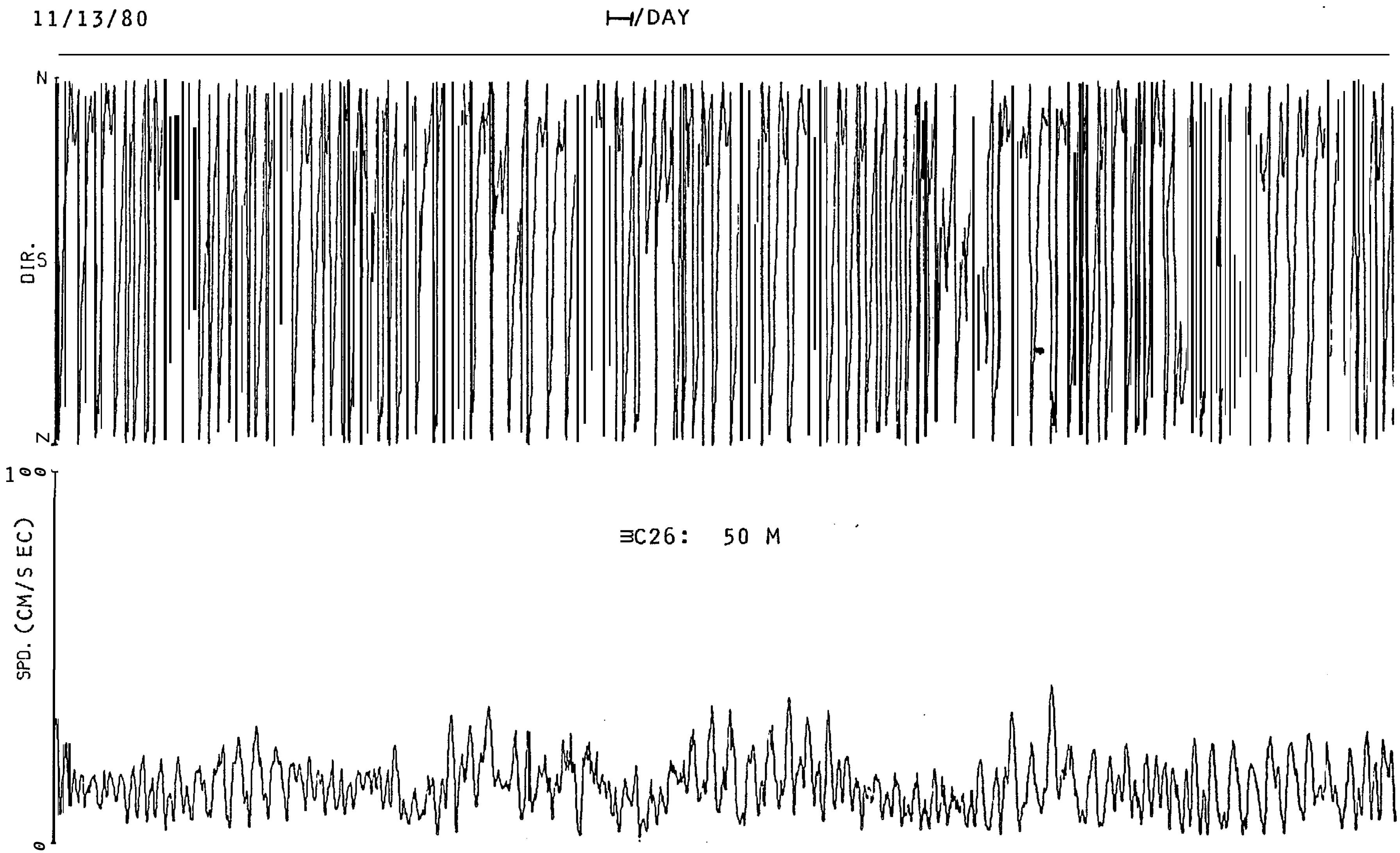

Figure 2-22. Same as for Figure 2-21, except that this record was from mooring BC26, the start date for the plot is 13 November 1981 and the segment plotted is 73 days in length.

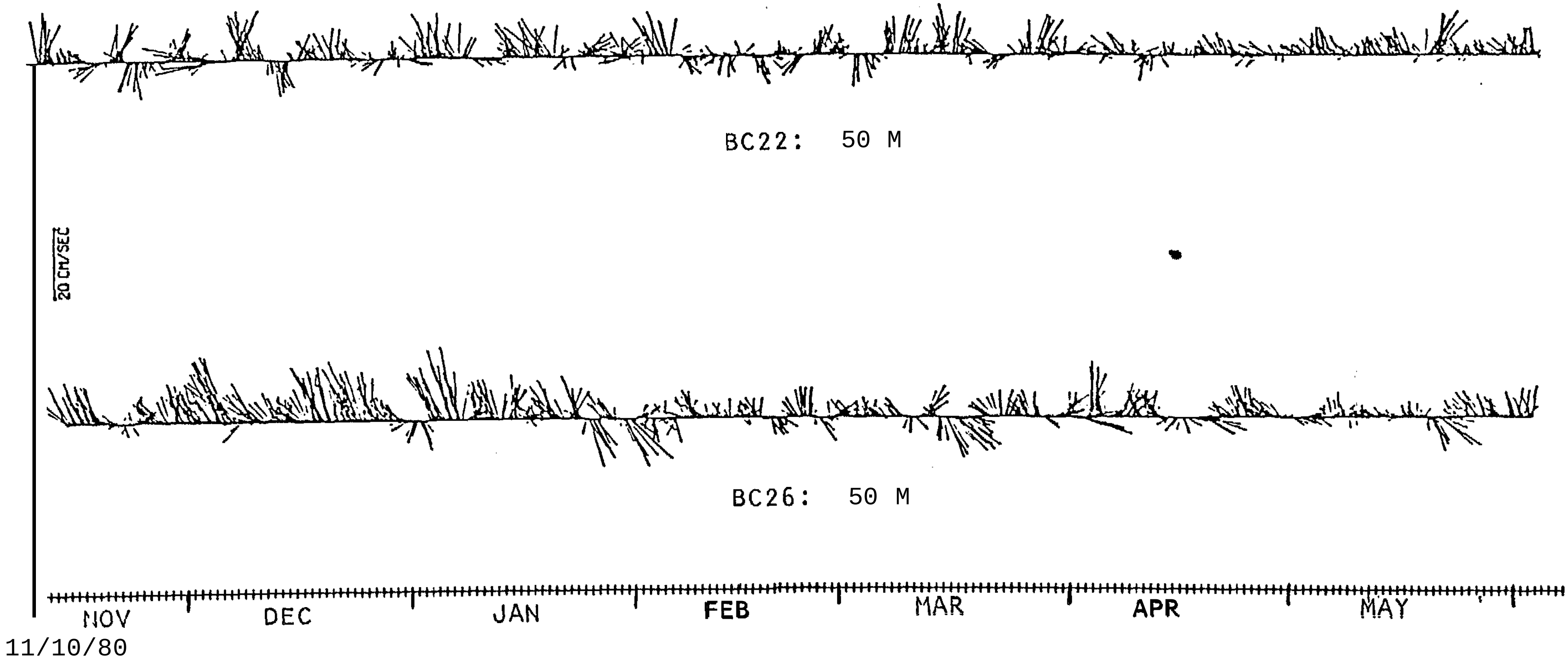

Figure 2-23. 35-hour filtered. current speed vectors plotted every six hours as a function of time for the 50-m deep records from moorings BC22 (upper) and BC26 (lower). Locations of moorings are shown on Figure 2-1 and geographical coordinates and other information are listed in Table 2-3.

frequent later in the record than near its beginning. These fluctuations are also apparent on the raw speed records (Figures 2-21 and 2-22), with the tidal currents appearing as high-frequency "noise" superimposed on the lower-frequency pulse.

In an attempt to estimate the significance of low-frequency (periods of 10 days or longer) flow fluctuations, monthly vector-averaged currents were computed for both moorings and are presented in Figure 2-24. While flow was northerly during all months, significant variations in east-west flow occurred from month to month. Comparison with the local bathymetry (shown as the local isobath direction at each mooring on Figure 2-24) indicates that the flow most strongly paralleled the bathymetry in November, December and May at both locations. The greatest deviation occurred at BC26 in March, when flow was completely across-isobath, onshore. These time-variations in along- and cross-shelf flow can also be depitted as plots versus time of the monthly mean along- and cross-shelf flow (Figure 2-25). Along-shelf flow was to the northwest for all months, though it was minimum through the mid-winter period February-April. Cross-shelf flow showed a clear tendency at both moorings to be off-shelf (to the southwest) early and late during the observation period, while flow was onshelf (toward the northeast) in mid-winter.

Temperature and salinity data obtained during February-March allowed qualitative comparison between the observed February-March currents at mooring BC22 and the internal density field. Figure 2-26 compares the computed baroclinic surface current with both the February-March and over-winter observed currents at 50-m depth. The computed surface flow paralleled the ice edge, while the observed current approximately paralleled the bathymetry. Since no current observations were obtained closer to the surface, it is impossible to rigorously compare magnitudes of the computed baroclinic and observed currents. The component

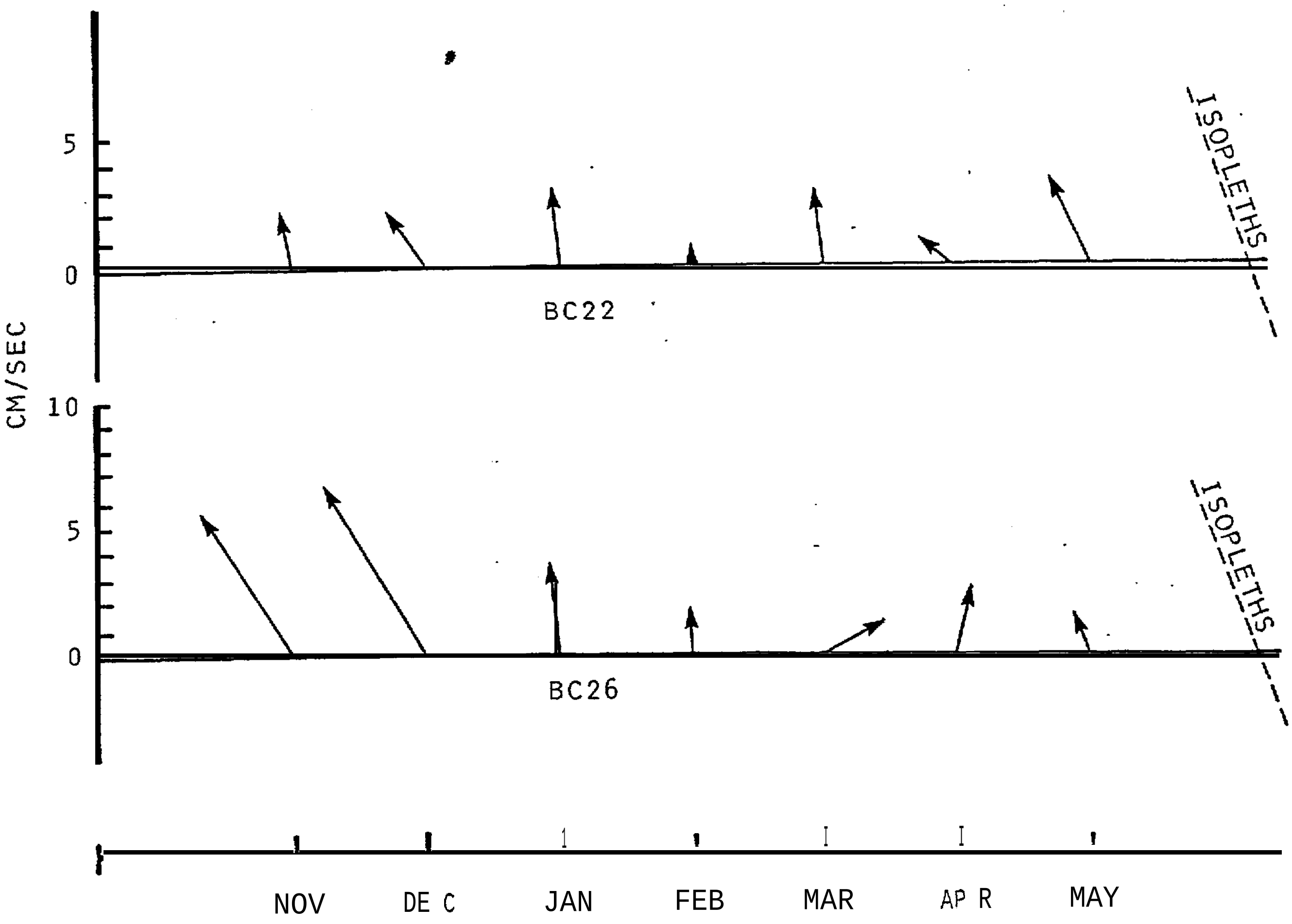

Figure 2-24. Monthly vector-averaged currents plotted as a function of time for the 50-m deep records from moorings BC22 (upper) and BC26 (lower). Dashed lines indicate direction of bottom isobaths at each mooring.

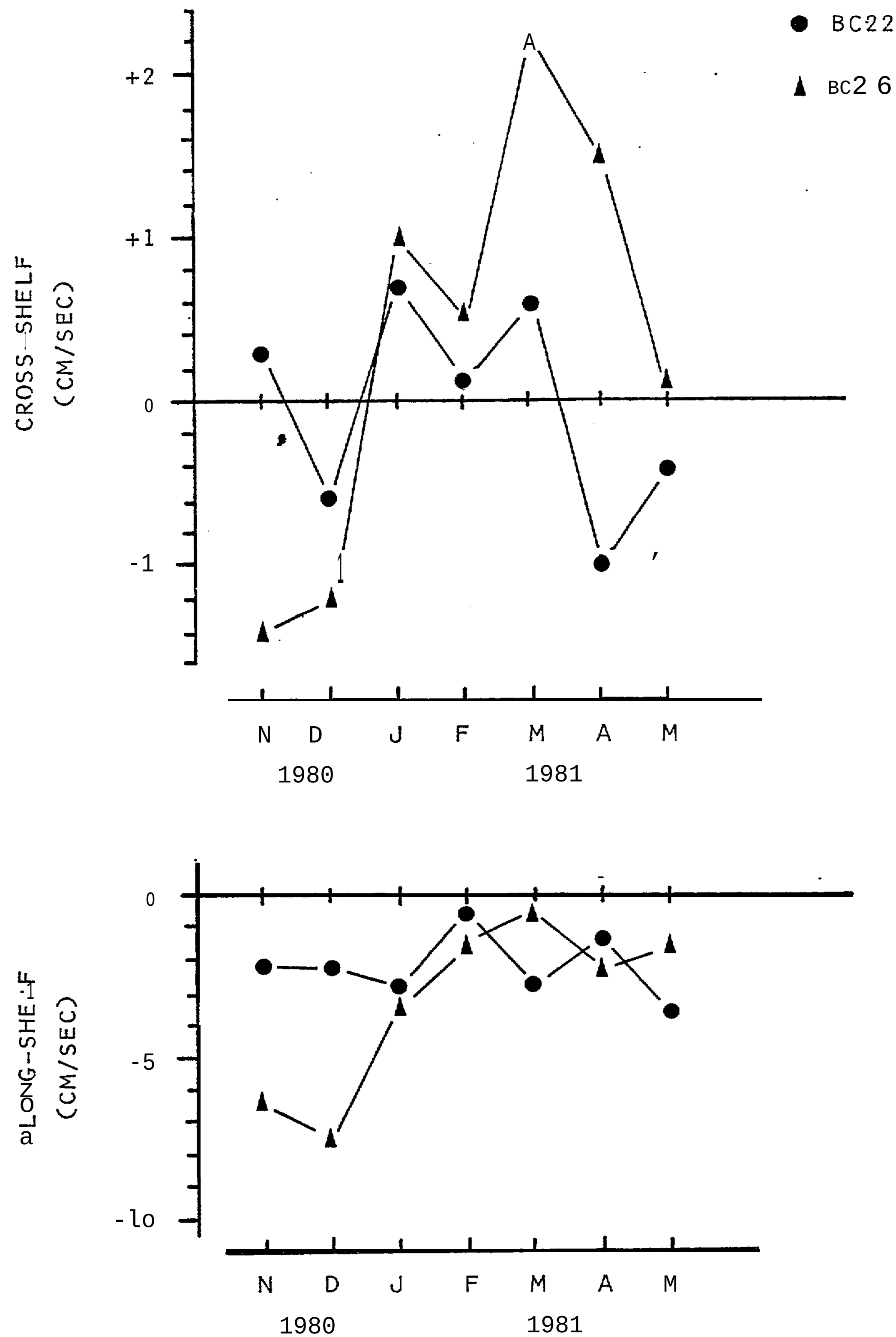

Figure 2-25. Plot as a function of time of the monthly mean cross-shelf (upper) and along-shelf (lower) current components derived from the 50-m deep current records at moorings BC22 and BC26.

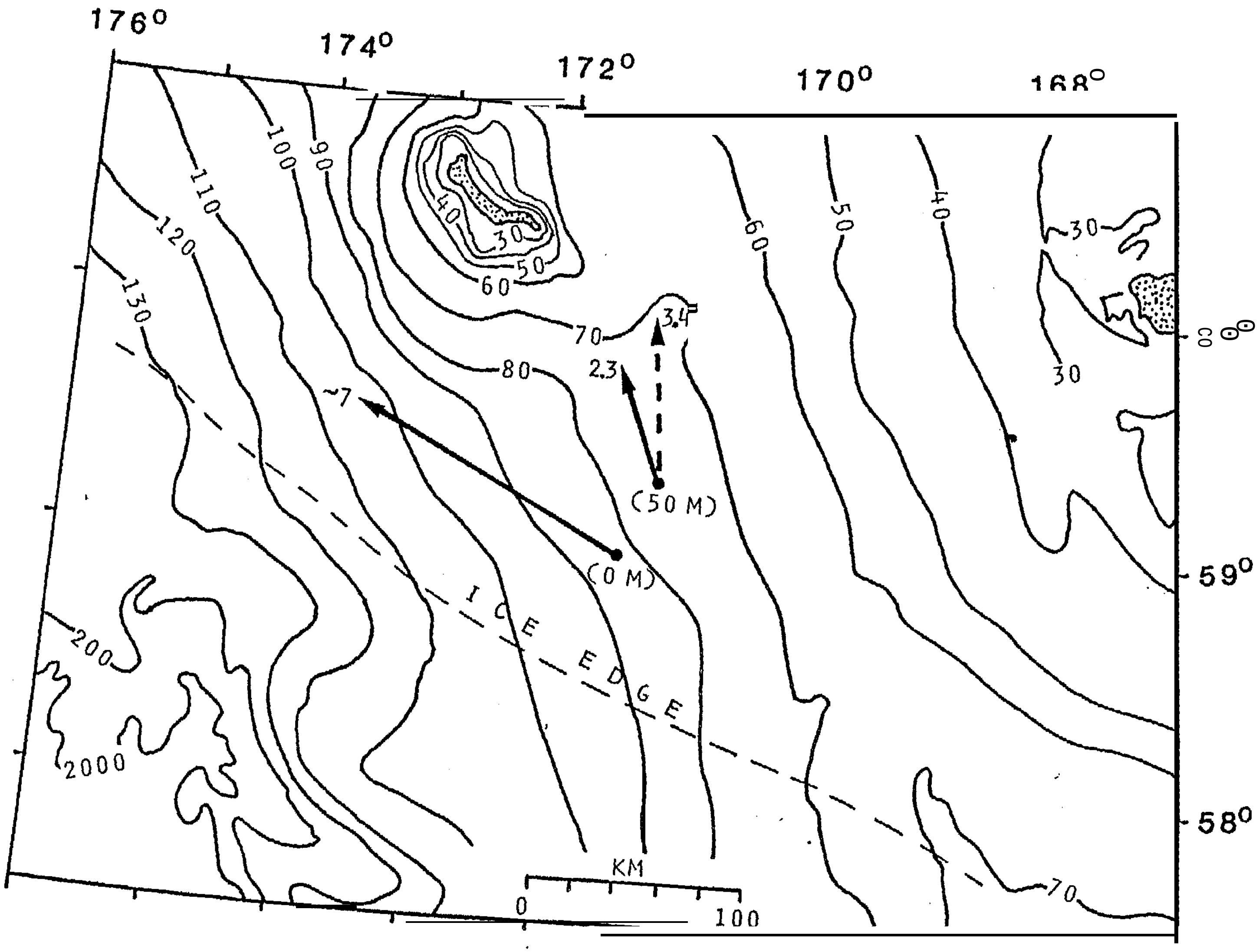

Figure 2-26. Comparison between implied mid-winter baroclinic surface current (arrow labeled "0 M"), vector-averaged over-winter current observed at 50-m depth at mooring BC22 (solid arrow labeled "50 M"), vector-averaged February-March current observed at 50-m depth at mooring BC22 (dashed arrow labeled "50 M"), and directional trend of local isobaths. Numbers at arrowheads refer to speed in cm/sec.

of the observed 50-m current parallel to the ice edge, hence, to the computed surface current, was about 1 cm/sec for February-March. Since this is of the same order as the computed surface current at the mooring (not shown on the figure), but was at 50-m depth rather than at the surface, the actual surface flow may have been somewhat larger than computed due to presence of a barotropic mode. Further discussion of these currents, within the context of regional oceanographic processes, is presented below in Section 2.5.

2.5. CONCLUSIONS

2.5.1. Discussion

The most significant contributions resulting from this program have been improved definition of the two-layered temperature and salinity structure associated with the ice edge in mid-winter, and the implications of this structure with respect to time-mean circulation and the ice edge location on the central Bering Sea shelf. This section will focus primarily upon these aspects of the results.

A schematic illustration of the extent of the two-layered structure on the Bering Sea shelf during mid-winter has been constructed using data obtained in March 1980 and March 1981 (Figure 2-27). The three crossings of the ice edge show, even though they were obtained during separate winters, a progressive divergence toward the west between the actual ice edge and the northern extent of the two-layered, subsurface water structure. The latter is seen, west of the Pribilofs, to approximately parallel the 100-m isobath. The ice edge, conversely, does not parallel the isobaths but extends farther south toward deep water over the western shelf. Historical analyses of the Bering Sea midwinter ice extent indicate that this is normally the case (Muench and Ahlnäs, 1976; Pease, 1980; Niebauer, 1981). The ice edge is well north of the shelf break in the eastern Bering Sea, whereas in the western Bering it extends well south of the shelf break and overlies deeper water.

The currents observed at 50 m during winter 1980-1981 paralleled isobaths, whereas the computed baroclinic surface currents paralleled the ice edge rather than the isobaths. This suggests that the location of the northern edge of the two-layered structure is controlled by the tendency for local currents to parallel isobaths, as observed. On the other hand, the computed baroclinic surface flow

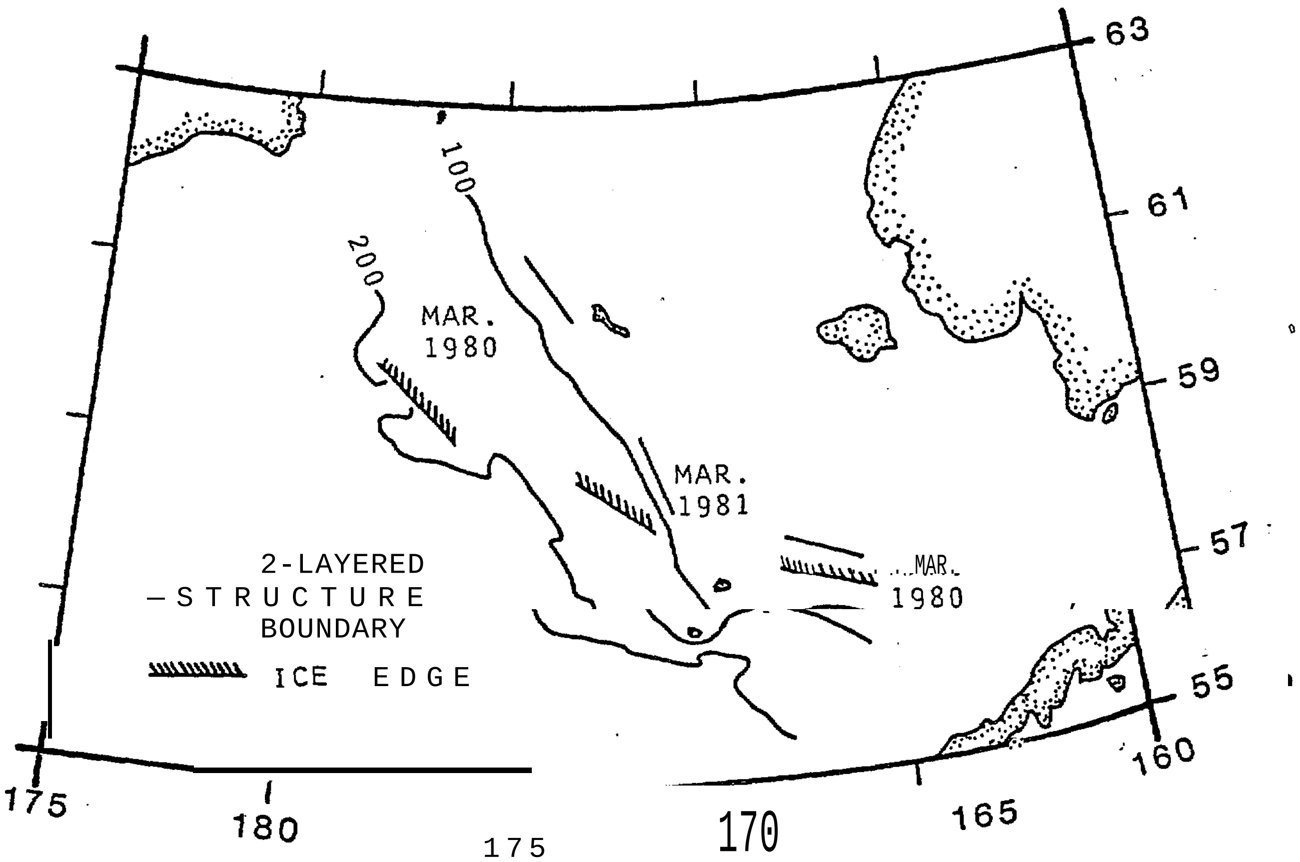

Figure 2-27. Schematic diagram comparing relationships between approximate ice edge locations and northern boundaries of two-layered water structure at three locations along the central Bering Sea shelf. The March 1981 data were obtained from this program, while the March 1980 data were derived from Newton and Andersen (1980). Bottom contour depths are in meters, with the 200-m isobath coinciding approximately with the shelf break.

would be somewhat decoupled from the bathymetry by the stratification between the layers, and would tend to follow a path related to the source of the bare-clinic field: the melting of ice along the ice edge.

At this point, it is necessary to speculate on processes which might control the location of the ice edge. In mid-winter, when air temperatures are generally below freezing, the time mean ice edge location must be controlled primarily by availability of heat from the underlying water column. This heat can be supplied by advection, or through horizontal and vertical turbulent diffusion. Presence of a 1-2 cm/sec current component, at 50-m depth, northward normal to the ice edge suggests one mechanism for advecting eat beneath the ice. The warm lower layer is, however, separated from the ice by a colder {approaching the freezing point at its northern edge), lower salinity upper layer. The interface between these layers is about 10-m thick. The density difference between layers varies from about 0.2 sigma-t units (observed in March 1981) on the central shelf up to more than 0.5 sigma-t units (observed by Newton and Andersen in March 1980) at the westernmost section on Figure 2-27. We hypothesize that, as the upper layer flows toward the northwest beneath the ice edge, its salinity is decreased by continual addition of low-salinity water derived from ice melt. This decrease in upper layer salinity increases the strength of the between-layer density interface, thus decreasing the upward flux of heat from the relatively warm, lower layer. This decreased upward heat flux allows the ice to extend farther southward before melting, as observed. Assuming a mean southward ice advection rate of 20 cm/see, which is reasonable based both upon data obtained during winter 1981 and upon historical data (Muench and Ahlnäs, 1976; Pease, 1980), about $0.5 \times 10^6 m^3/sec$ of meltwater derived from sea ice is added to the upper layer between the easternmost and westernmost sections shown on Figure 2-27. This is of the same order as the computed baroclinic flow through the winter 1981 section and, clearly, is sufficient to strongly impact the regional salinity (hence density) field.

The westward baroclinic flow associated with the ice edge appears to be a . consequence of the local input of low-salinity water due to ice melting. It is this consistent westward flow which leads to the above mechanism allowing the ice to extend into deeper and deeper water toward the western side of the Bering shelf. Presence of this baroclinic field and its associated flow also suggests a reason for the relatively constant location of the two-layered structure, despite large north-south excursions, of the ice edge. The ice edge excursions occur over time scales of a few days, as was graphically demonstrated during February-March 1981 (see Figure 2-17). The baroclinic response time of the water column is, however, longer. It is not likely that the two-layered structure would respond to single storm events. While it is generally recognized that the year-to-year variability in maximum southward extent of the ice edge is a function of the severity of the winter, and that short-term fluctuations in ice extent may occur in response to discrete storms, it now appears that fluctuations of ice edge location over time scales of several weeks are probably damped by the combined response time of the baroclinic field associated with the ice edge and the vertical density structure associated with this field. If ice is advected rapidly southward over the higher temperature water in the southern part of the two-layered structure, it will melt and soon return to its original location. On the other hand, a short term retreat of the ice would place it over water at or near the freezing point. Northeasterly winds, which prevail over the Bering Sea in winter, could then rapidly advect it southward to its equilibrium location without appreciable melting. Freezing of ice in the region overlying the layered structure would release salt into the water and decrease the density difference across the interface. This would allow, in turn, increased upward heat flux which would act to slow the freezing process. Increased melting, conversely, would add low salinity water to the upper layer, increase the strength of the interface and decrease upward heat flux available to melt the ice.

It was noted above (Section 2.3.3) that water on the central Bering shelf had temperature-salinity characteristics similar to those of Alaska Stream/Bering Sea Water rather than the Bering Shelf Water defined by Kinder and Schumacher (1981) using data obtained farther to the southeast. This difference was due to the salinity, which was 1-1.5 O/oo higher on the central than on the southeastern shelf. Part of this difference may have been seasonal, since" Kinder and Schumacher used spring and summer data which would have included maximum freshwater admixture from terrestrial sources. It also seems reasonable, however, that the flow of deep layer, oceanic water beneath the ice edge as observed would, through admixture with the upper layers, increase the salinity of the shelf water over that observed to the southeast.

The above discussion qualitatively relates the observed ice edge location, currents and the temperature, salinity and density fields on the central Bering Sea shelf. Quantification and rigorous testing of these hypotheses require additional field data, particularly with respect to the vertical and horizontal definition of the observed currents, and are beyond the scope of the present treatment.

2.5.2. Summary

The results of the physical oceanographic investigations carried out in support of the overall Bering Sea MIZ program may be summarized as follows:

- The central Bering Sea shelf region was characterized in November 1980 and February-March 1981 by a water structure vertically two-layered in temperature, salinity and density. In November, this structure covered the entire shelf. In February-March, the structure was restricted to a band about 80-km wide which underlay the ice edge.

- Associated with the two-layered structure in winter was a northwesterly baroclinic surface current having maximum speeds of about 7 cm/sec relative to the 75 db level. Northwestward baroclinic volume transport relative to the same level was of order 0.5 x 106 m^3/sec.

- Observed over-winter mean currents at two locations on the central Bering Sea shelf at 50-m depth were 2-3 cm/see, with flow along-isobath to the northwest in agreement with conventional wisdom on Bering shelf circulation. These mean flow speeds were somewhat higher than those which have been previously reported farther to the southeast on the shelf.

- Fluctuations, having time scales of 7-10 days, were present in both speed and direction at both current moorings, and led in several instances to reversals to southeastward flow.

- Monthly mean observed currents were all alongshelf toward the northwest; however, cross-shelf components fluctuated from month-to-month with maximum on-shelf flow in mid-winter.

- Tidal currents were 20-40 cm/sec east of St. Matthew Island and were 10-30 cm/sec west of it. Tides were mixed, predominantly diurnal.

- Overall temperature-salinity characteristics on the central shelf in both November 1980 and February-March 1981 were similar to those of Alaska Stream and Bering Sea Water, rather than to Bering Shelf Water as defined farther to the southeast.

- A hypothesis is developed which qualitatively interrelates the ice edge location and the observed temperature, salinity and current fields in terms of stability of a baroclinic current which is maintained by the ice edge, under-ice heat advection by near-bottom flow and control over vertical heat exchange by a density interface.

Acknowledgement

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