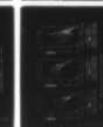
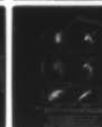
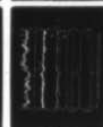
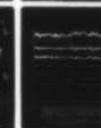
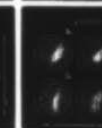
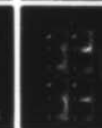
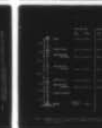
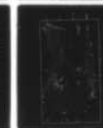


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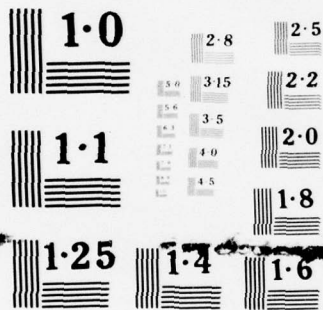
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## CURRENT METER AND TEMPERATURE RECORDS FROM THE WINDWARD PASSAGE

By

William G. Metcalf, Marvel C. Stalow  
and Marguerite Samanovic

July 1977

### TECHNICAL REPORT

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February and March 1974, additional bathymetric and hydrographic station observations were made and the current meters and temperature recorders were recovered. In this report, some of the basic data from the moored arrays are presented.

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Department of Physical Oceanography

## ABSTRACT

During late 1973 and early 1974, current and temperature measurements were made close to the sill of the Windward Passage between Cuba and Hispaniola. In the course of ATLANTIS II Cruise 78 in November 1973 a brief bathymetric survey of the sill area was carried out followed by the anchoring of two arrays of current meters and temperature recorders. Hydrographic stations were occupied in the sill region to determine the temperature, salinity, oxygen and silicate characteristics of the water column. During KNORR Cruise 37 in February and March 1974, additional bathymetric and hydrographic station observations were made and the current meters and temperature recorders were recovered. In this report, some of the basic data from the moored arrays are presented.

## INTRODUCTION

From early November 1973 to early March 1974, current and temperature measurements were made in the Windward Passage between Cuba and Hispaniola close to the sill of the ridge separating the North Atlantic Ocean from the Cayman Basin in the western Caribbean Sea. In the course of R/V ATLANTIS II Cruise 78, a bathymetric survey of the sill area was carried out followed by the anchoring of two moored arrays of vector averaging current meters (VACM's) and temperature/pressure (T/P) recorders on the 10th of November 1973. During this cruise, hydrographic stations were occupied in the sill area to determine the temperature, salinity, dissolved oxygen and dissolved silicate characteristics of the water column. In February and March 1974 the R/V KNORR, on Cruise 37, operated in the Windward Passage area and additional bathymetric and hydrographic observations were carried out. On 2 March, the current meters and temperature/pressure recorders were recovered.

Listings of the hydrographic station data along with sectional profiles of the temperature, salinity, oxygen and silicate are given in Metcalf, Stalcup and Zemanovic (1974). The results of the bathymetric surveys are reported in Metcalf and Stalcup (1976). The bathymetric

chart of the area showing the locations of the moored arrays presented here as Figure 1 is from this latter report. As shown in the chart, the sill was found to be 1560 m in depth, and the current meters were anchored about 3.3 km apart very close to the sill. One array, #504, was placed in 1539 m of water very slightly to the west of the saddle point. The other was in 1543 m on the eastern side of the deepest channel and slightly on the Caribbean side of the ridge.

The instruments were arranged identically in the two moored arrays as shown diagrammatically in Figure 2. All the instruments were recovered and usable records were obtained for at least part of the time in all cases. Table 1 gives the details concerning the positions, depths, and quality of the records from all the instruments. For this report, the data records have been computer-processed using relatively simple programs to demonstrate the type and quality of the data, the basic type of flow in the passage and the fundamental relationship between the flow and the temperature regime.

## RESULTS

Progressive vector diagrams for all 4 current meters are presented in Figure 3. The vectors of the two deep current meters (#5044 and #5054) are shown emanating from a common origin representing the 10th of November 1973. The two records show many basic similarities, the major difference being that the inflow direction of #5044 is almost due south while that of #5054 is about  $20^\circ$  to the right ( $200^\circ$  True). In Figure 1, it can be seen that mooring #504 is close up against the slope on the west side of the sill, and this may effect the direction the inflow can



TABLE 1

Lat. 20° 18' 8" N	Water Depth	Launched 10 Nov. 1973	Lat. 20° 17' 5" N	Water Depth
Long. 73° 38' 8" W	1539 m.	Recovered 2 Mar. 1974	Long. 73° 37' 5" W	1543 m.
112 days of record				

Depth (m)	Instrument Serial #	Remarks	Instrument	Depth (m)	Instrument Serial #	Remarks
1076	5041	good	VACM	1080	5051	fair (4)
1079	5042	good	T/P	1083	5052	calibration error (5)
1278	5043	fair (1)	T/P	1282	5053	good
1487	5044	poor (2)	VACM	1491	5054	good
1490	5045	short (3)	T/P	1494	5055	good

- 3 -

- (1) #5043 T/P - did not record below 4.18° C due to improper setting.  
 (2) #5044 VACM - suffered from intermittent malfunctioning. Also, the last 31 days of record are unusable.  
 (3) #5045 T/P - ceased functioning on 1 Dec. 1973 (21 days of record).  
 (4) #5051 VACM - jammed at start: freed itself by 10 Dec. 1973 (lost first 30 days of record).  
 (5) #5052 T/P - faulty calibration. Temperatures have been corrected by -0.25° C.

take. The other deep current meter, being alongside a less steep slope was in a current less restrained by the topography. In both cases, the outflow is directed towards about  $035^{\circ}$ . The major features such as the gross changes in direction and speed are virtually identical in both deep records.

Comparing anything but the major patterns of these two instruments must be done with caution because of an intermittent electronic malfunction which plagued instrument #5044. During certain periods of time which are indicated by brackets in Figure 3, the instrument was operating erratically, and on the 31st of January it ceased functioning entirely thus losing the last 31 days of current records. For those periods of erratic behavior, the computer program continued calculating progressive vectors on the basis of the last "good" observation. In a record marked by fairly large natural fluctuations this obviously has the potential for introducing major aberrations in the diagram. However, the pattern as a whole shows such a consistent resemblance to that of instrument #5054 that it was decided to include the material in the diagram, calling attention to the problem and to the periods involved.

Shallow current meter #5051 suffered from some kind of malfunction for the first 28 days it was in place, possibly due to a bit of weed getting jammed in the rotor. Whatever the cause, it spontaneously cleared itself by the 10th of December. In the progressive vector diagram, the two shallow records (#5041 and #5051) are shown with the 10th of December as a common point. From that point to the end of the records, the main events are very much the same in both records.

The two shallow records resemble each other in their grosser details as do the two deeper ones. In general, events appearing as major changes in the characteristics of the flow occur simultaneously on all 4 of the records. At both levels, the current at the west side (instruments #5041 and #5044) was directed somewhat to the left of that on the east side and this difference was more pronounced on the inflowing current than on the outflowing current, as is shown in Table 2.

As is shown in Figure 3, up until the 4th of January, the predominant flow at both levels at both moorings was into the Caribbean. The inflow at the bottom was appreciably stronger than that 400 m above it.

On 4 January, a major change occurred in the gross pattern. At the shallower depth, the predominant flow was out of the Caribbean until the end of the record, although after the 17th of January, the pattern again changed appreciably. At the deeper level inflow and outflow alternated irregularly after the 4th of January with neither being greatly predominant. The most general statement that can be made is that over the entire period of approximately 112 days, outflow exceeded inflow at 1100 m, and inflow exceeded outflow at 1500 m.

This shows particularly clearly in the scatter diagrams in Figure 4 A-D in which current speed is plotted against direction of flow. Each dot in the diagrams represents the average speed and direction over a period of an hour. In the records from the two shallow meters (#5041 and #5051, Figures 4 A-B) the highest speeds are in the outflow sectors. In the cases of the deeper meters (#5044 and #5054, Figures 4 C and D) the highest speeds as well as by far the greatest concentrations of dots are

TABLE 2

Major flow directions in the 4 current records.

#5041 (West)	SHALLOW	#5051 (East)	Difference (E-W)
	inflow		
	outflow		
195°		210°	15°
055°		065°	10°
#5044	DEEP	#5054	
	inflow		
	outflow		
180°		200°	20°
020°		025°	5°

NOTE: These directions are only approximate, having been determined from the progressive vector diagram (Figure 3) with a straight-edge and protractor and rounded off to the nearest 5° of azimuth.



in the inflow sector. The effect of the restricting influence of the sides of the channel at the greater depths is reflected in the distribution of dots between the inflow and outflow sectors. In the case of #5054 at the eastern side of the channel, an appreciable flow to the west and northwest is possible whereas this type of flow is blocked by the steep western slope of the channel in the case of the current meter (#5044) moored close to that slope. Another presentation of the same information is given in Figure 5 A-D with the current speed plotted vs. direction in a polar projection.

In Figure 6 A, hourly averages of current speed and temperature have been plotted vs. time for the shallow instruments at the western mooring. In the cases of the currents, the speed is shown in terms of North-South (outflow-inflow) and East-West (cross-channel) components. This is accomplished by "rotating" the directional field in the current records to compute the vectors aligned with the major flow axes. In each case, positive direction represents outflow, and negative represents inflow. In the case of the cross-channel vectors, positive is to the right of the outflow direction and negative to the left. In addition, the amount of rotation was changed part way through each record to adjust to the marked change in the character of the flow that occurred on 4 January and that shows clearly in the progressive vector diagrams (Figure 3). The amount of rotation for each portion of the current record is indicated in the figure.

The high degree of variation on the hourly averages is striking. The very pronounced semi-diurnal tidal signal is the most obvious pattern

superimposed on the much longer inflow-outflow cycle in the case of the current and on the temperature cycle.

In order to remove some of the short period variability such as the tidal signal, for example, the data were put through a "low pass filter" (Schmitz, 1974) which gives, in essence, a running average of 24 successive hourly averages. This produces the greatly smoothed records shown in Figure 6 B and a different view of the overall relationship between temperature fluctuations and the current is gained.

Figures 7, 8 and 9 show the same information for the other current meter/temperature recorder sets.

Figure 10 shows the temperature vs. time plots of the intermediate temperature recorders which were not accompanied by current meters. Attention must be called to the record of instrument #5043 (western mooring) the squared-off effect at the lower temperature ranges stems from the fact that the instrument was adjusted improperly and did not record potential temperatures below about 4.18° C.

To illustrate further the relationship between the water movements and temperature fluctuations, hourly averages of current direction have been plotted by computer in a scatter diagram against corresponding hourly averages of potential temperature. Figure 11 demonstrates this relationship in three sets of current direction vs. temperature plots. (The 4th set is not usable because of the early failure of temperature recorder #5045.) In each set, heavy concentrations of dots mark the major inflow and outflow directions. However, the clear predominance of the inflow and outflow characteristics of the current which is so

clearly shown in the progressive vector diagrams (Figure 3) does not appear as clearly here because in this representation only the direction is shown without any speed factor. In other words, the fact that the greatest speeds and therefore the greatest flows are in the inflow and outflow directions is lost in this diagram. Nevertheless some interesting information is revealed by the current direction/potential temperature relationship.

The two shallow sets of records (instruments #5041/42 and #5051/52, Figure 11 A-B and C-D) show patterns closely resembling each other but quite different from the patterns found in the deeper set (instruments #5054/55, Figure 11 E-F). One noticeable feature in the shallow sets is that the temperature range of the outflowing current is greater than that of the inflowing current. This may be associated with the fact that at this level, the outflow exceeded the inflow during the nearly four months of observation as is shown clearly in the progressive vector diagrams (Figure 3). The excess water exiting the Caribbean at this level over that entering was drawn from both slightly shallower (warmer) and slightly deeper (cooler) levels of the water column.

The deep set of records shows quite a different pattern. In the first place, because the channel narrows near the bottom, much less cross-channel flow is seen. The main difference is that the temperature of the outflow is distinctly warmer than that of the inflow. This suggests that the situation is similar to that at the Jungfern Sill where the coldest incoming water flows to lower levels after passing the sill so that when the current reverses, this cooler water is not

involved in the outflow. (See Sturges 1970, 1975 and Stalcup, et al, 1975.)

At the right hand side of Figure 11, the same data that made up the scatter diagrams were put through the "low pass filter", described earlier as producing 24 hour running averages of the hourly averaged data. Concentrations of dots again show the outflow and inflow conditions. In these filtered sets it can be seen much more clearly than in the unfiltered sets that the temperature of the outflow has a much higher range than is found in the inflow in the two shallow sets of records (Figure 11 A-B and C-D) while the opposite conditions is present in the deeper set (Figure 11 E-F). In passing, it is interesting to note that in the 24 hour running averages, both the shallow current meters show that the turning of the current from inflow to outflow and back always went through the SE quadrant and never the northwest one. The deep current, on the other hand, generally went through the northwest quadrant and only once did it appear to rotate through the southeast quadrant. This is the deep current meter on the eastern side of the channel, and we feel the local topography was responsible for this feature. It should be mentioned that this does not mean that the current never swung through the NW section in the shallow layers or only once through the SE sector in the deep layer. It simply means that whenever the current swung through those sectors it did so relatively rapidly so that it does not register in the 24 hour running averages.

Figure 12 shows the "inflow-outflow" vectors of the two shallow and one deep current record plotted against potential temperature. To



get the vectors, the current direction data were rotated. This could not be done as it was in Figures 6 thru 9 where the degree of rotation was changed part way through the record when the pattern of flow changed. In Figure 12 a mean rotation was used for the entire set of data in each case.

In the two shallow sets of data (Figure 12 A-B and C-D) the scattering of dots at first glance seems to be pretty random. However, it can be seen that both the highest and the lowest temperatures are found in the outflow (positive) part of the diagram. When the same data are filtered, this feature is greatly emphasized as is seen in the right hand set of graphs in Figure 12.

In this type of presentation the difference between the shallow and deep sets is quite strongly evident. Figure 12 E showing the unfiltered data of inflow-outflow vectors vs. potential temperature for the deep set of instruments, a definite slope can be seen indicating that on the average the inflow (negative velocity) is colder than the outflow. Filtering the data produced Figure 12 F which shows that when the data are averaged over 24 hours, there is a very close relationship - cool inflow/warm outflow, and that the very coldest temperatures accompany the highest inflow velocities.

The series of diagrams presented as Figures 13 thru 18 shows the energy spectra of both the current and temperature records. The computer program, using the Fast Fourier Transform Algorithm (Singleton, 1969) is described by Tarbell (1974). The data are dealt with in such a way that the tidal (both diurnal and semi-diurnal) and inertial periods are resolved.

In the case of each current meter record, the energy of the north-south

and east-west components are presented separately and in combination. The directions have been rotated as described earlier so that the north-south direction is aligned with the general outflow-inflow axis.

The diagrams will not be discussed individually, but a few generalizations and comparisons can be made. In every case in both the current and temperature records, the semi-diurnal and diurnal tidal periods of about 12.5 and 25 hours respectively are represented by prominent energy peaks. Lesser distinct peaks at periods of 6 and 8 hours may represent harmonics of the tidal periods. In most but not all the diagrams, a distinct peak or at least a noticeable "shoulder" in the curve is present at a period of 35 hours representing the inertial period for this area.

In the current records, the energy in the tidal periods are roughly an order of magnitude greater in the outflow-inflow direction than in the cross channel direction. The tidal energy is roughly the same in the shallow and deep records, but the inertial period is definitely more pronounced in the shallow than in the deep records.

For reasons we cannot explain one or more peaks or prominent shoulders appear at periods between 50 and 100 hours in the shallow eastern current records, and in the intermediate eastern and deep western temperature records. Two of these, shallow eastern current meter (#5051) and the deep western temperature recorder (#5045) were short records, but the intermediate eastern temperature record was full length and of good quality.

Some of the differences among the various sets of energy spectra

are probably attributable to the fact that the records varied in length. The method used produces greater smoothing in the longer records where a higher number of "pieces" of the record were used in the averaging process.

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NOOO 14-66-CO241 NR 083-004. The temperature/depth recorders were loaned to us through the kindness and cooperation of Dr. John Dahlen of the Draper Laboratory, Massachusetts Institute of Technology.

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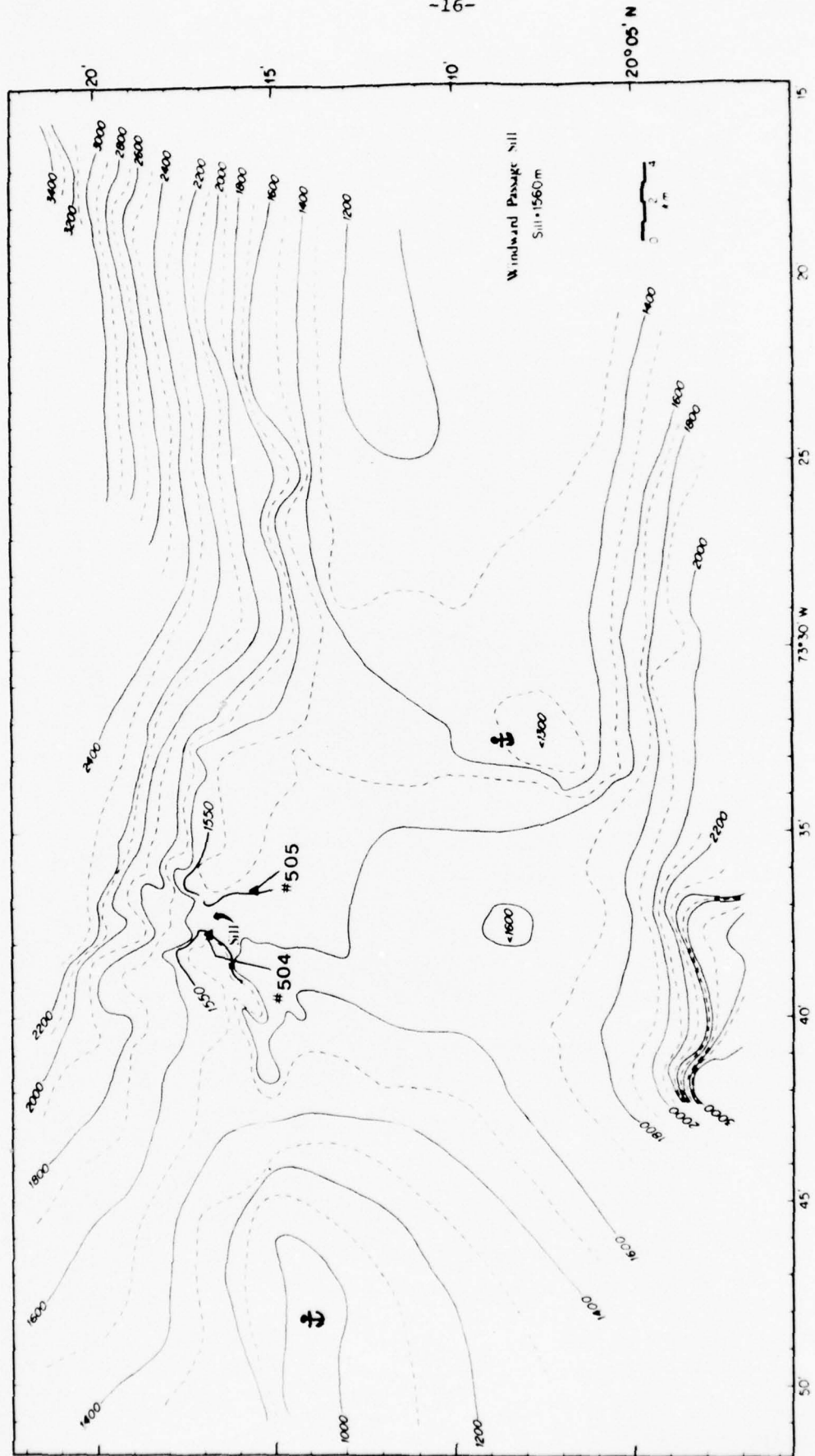


FIGURE 1 Windward Passage area showing locations of moored instruments. Anchor symbols indicate special navigational markers used in the bathymetric survey. (Bathymetry from Metcalf and Stalcup, 1976.)

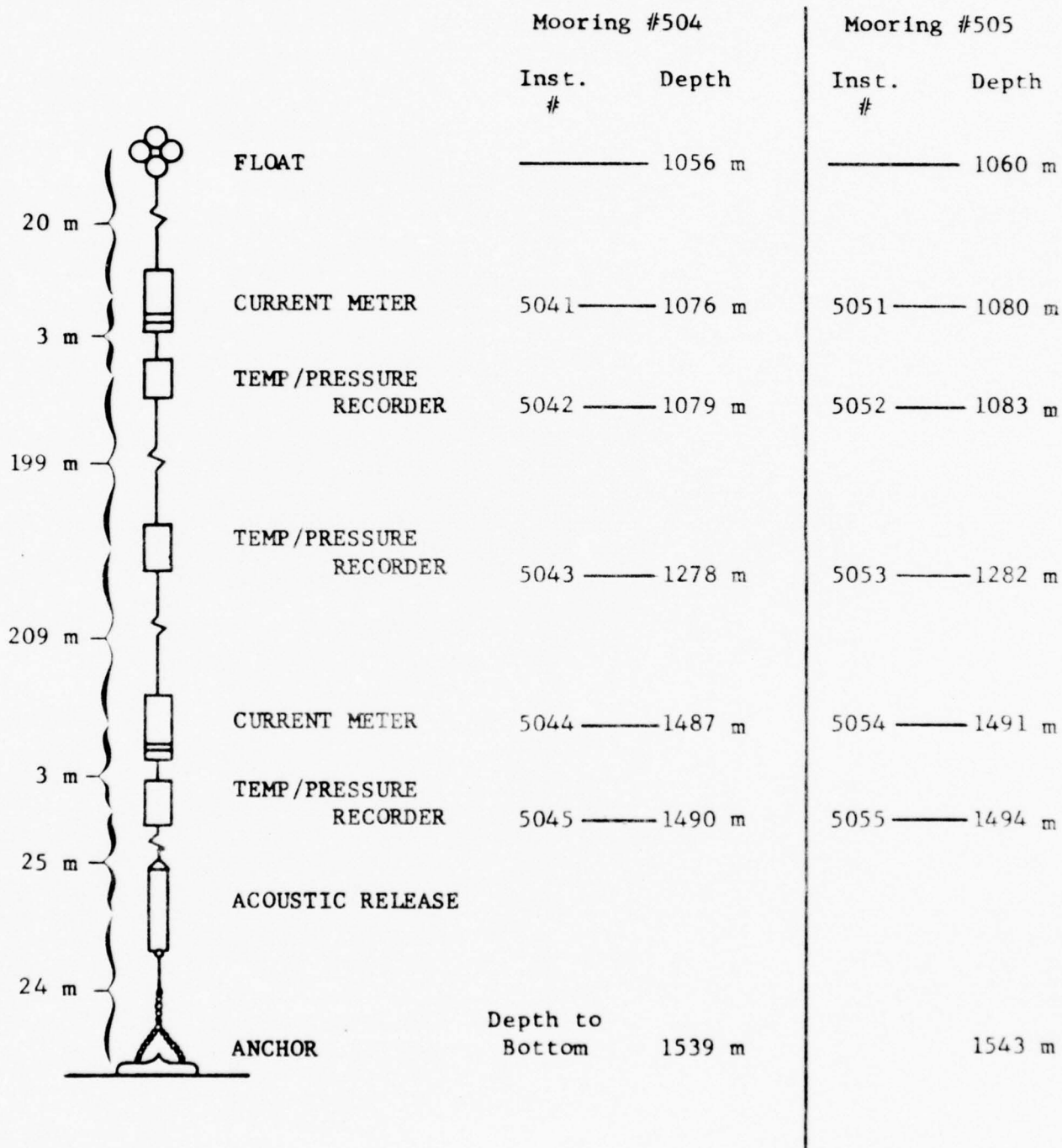


FIGURE 2 Diagrammatic sketch of the instrument moorings. Mooring #504 was about 3 km northwest of #505. See Figure 1 for locations of the instruments relative to the local topography.

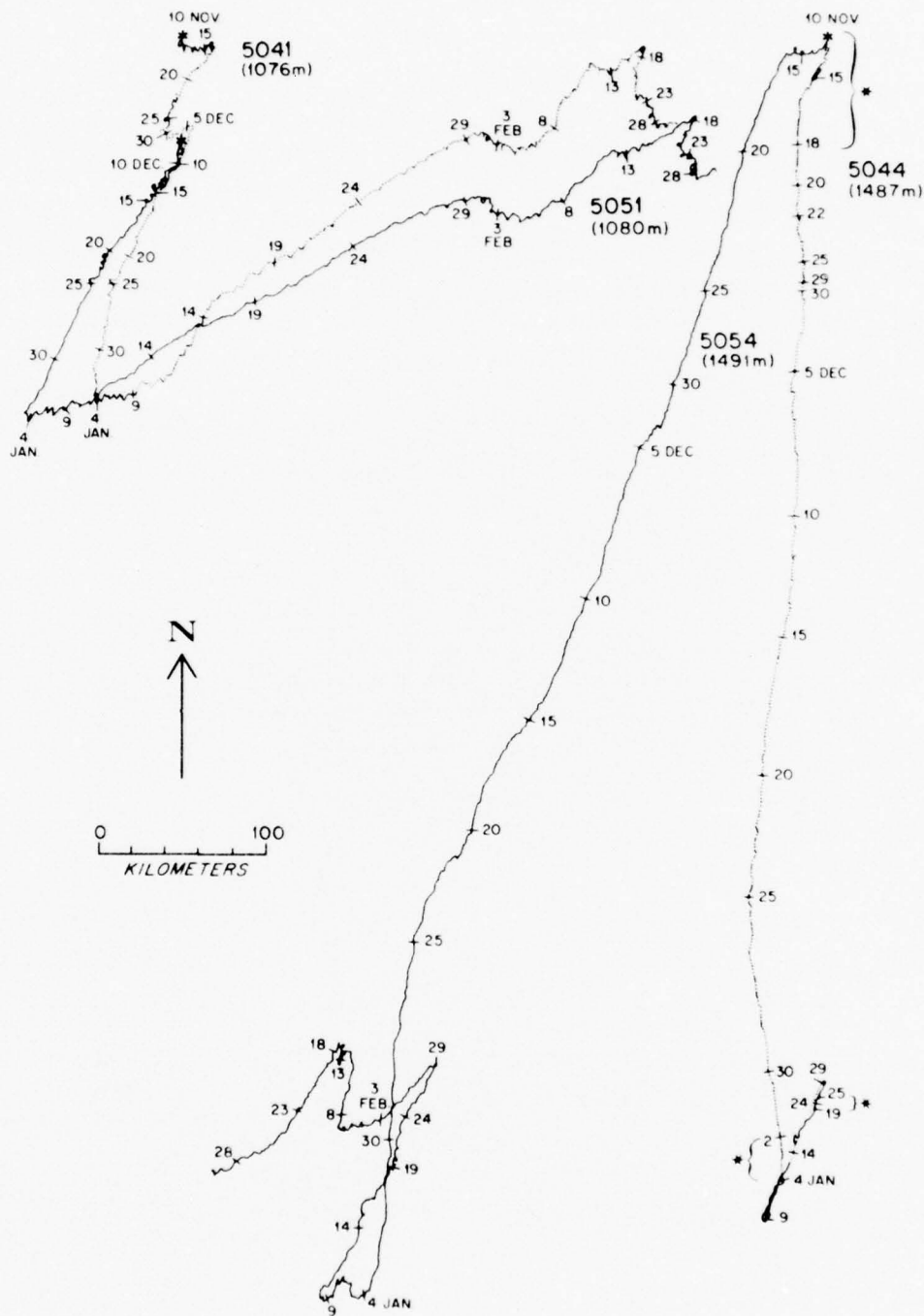
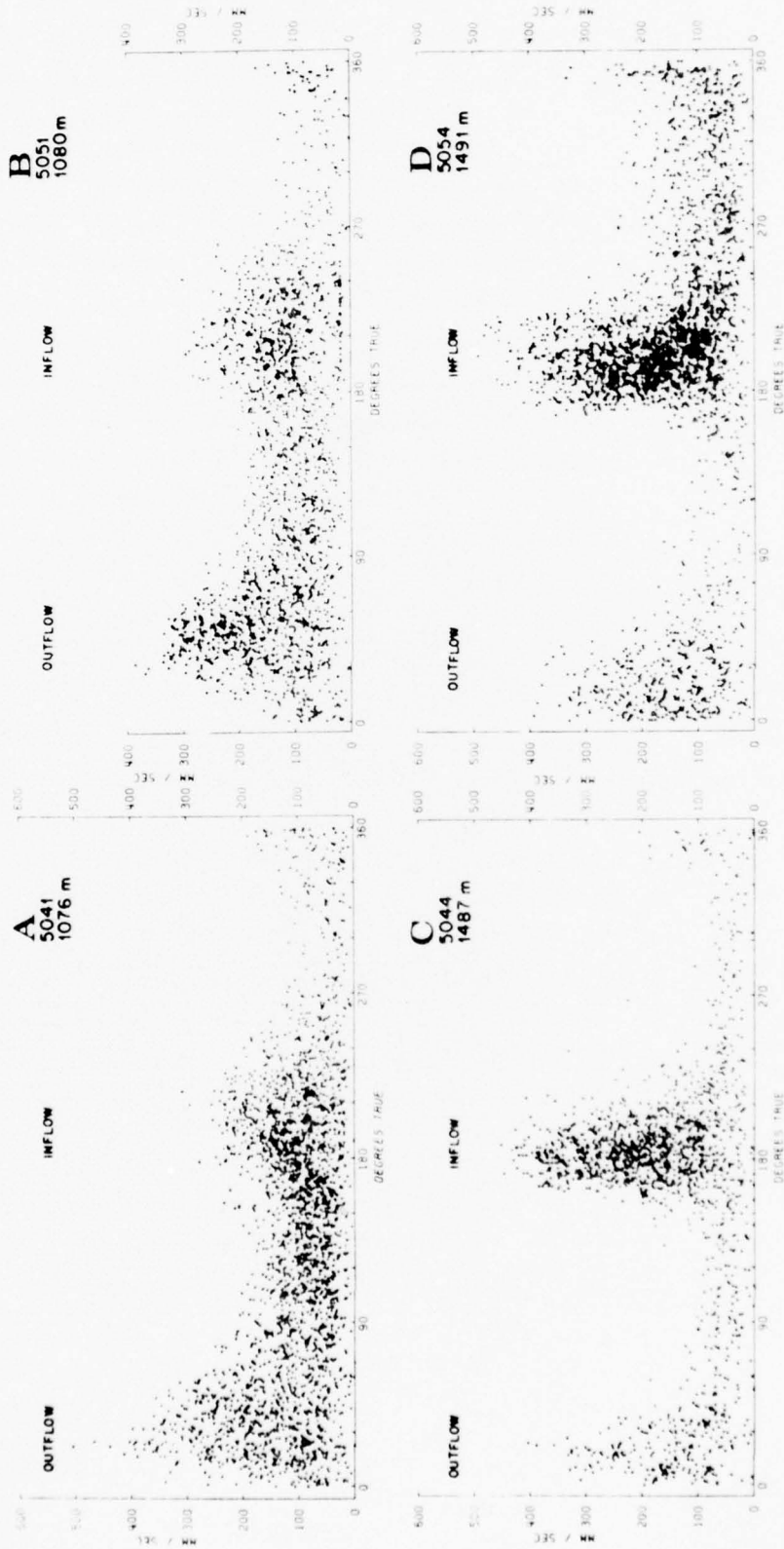


FIGURE 3 Progressive vector current diagrams. Records #5041 and #5044 are from the west side of the channel; #5051 and #5054 from the east. (See Figures 1 and 2 for locations and details.) For comparison purposes, the shallow records are shown with the 10 December points in common due to a faulty record in #5051 before that date. The deep records show 10 November as the common origin. Deep instrument #5044 suffered intermittent periods of malfunctioning indicated by brackets with stars.



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FIGURE 4 Scatter diagrams of current speeds vs. direction. Each + represents and hour's average.



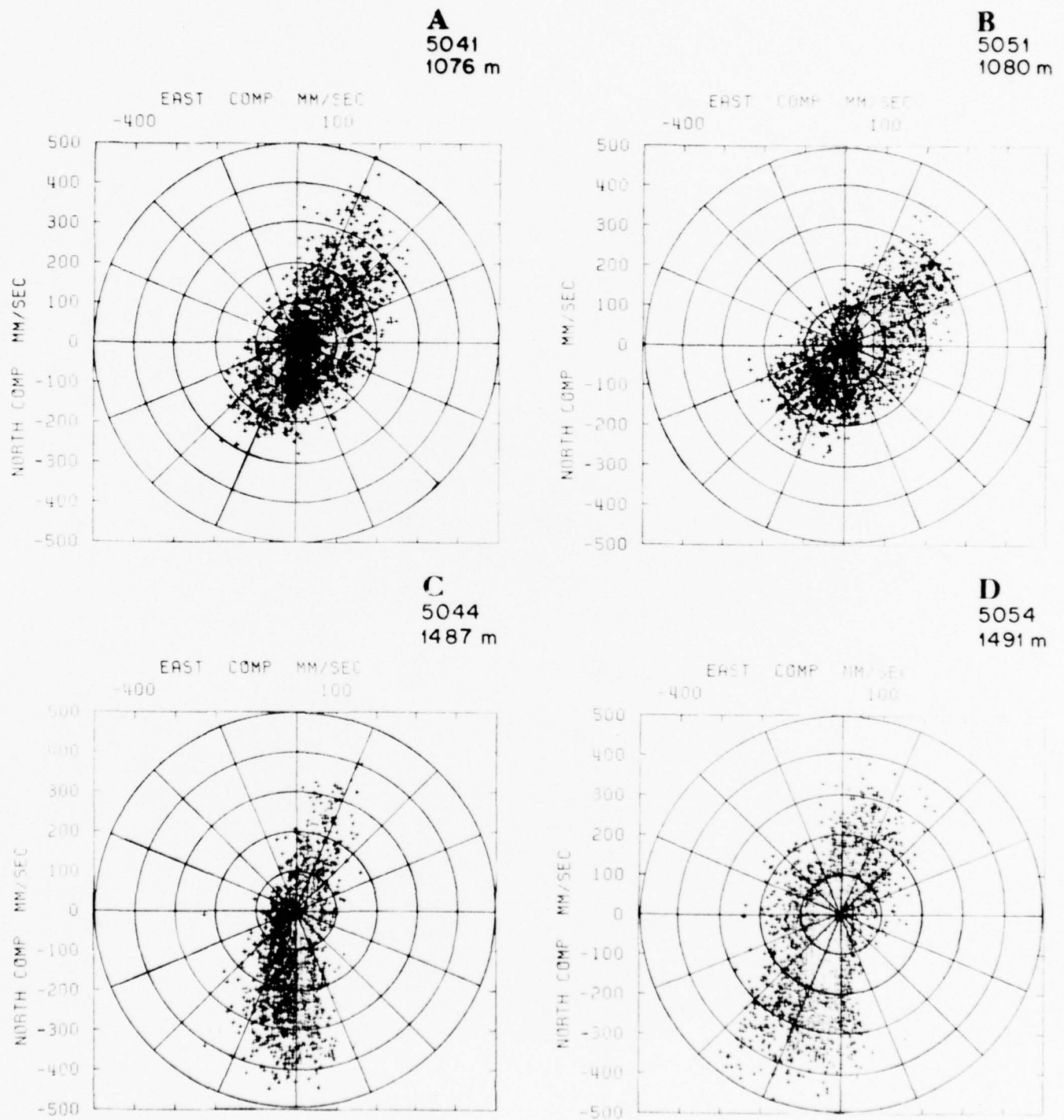


FIGURE 5 "Polar Projection" of the same data sets shown in Figure 4.

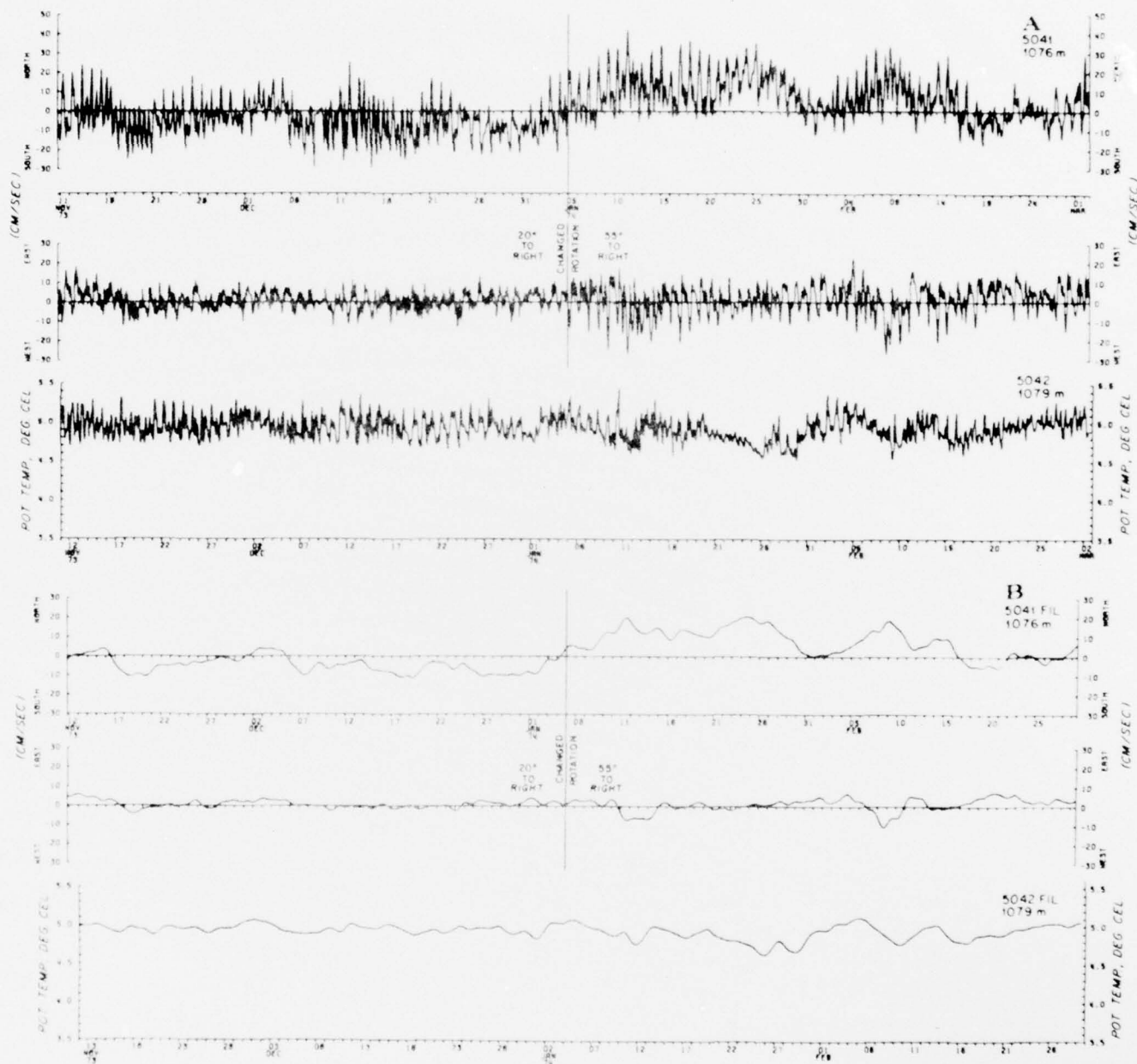


FIGURE 6 Shallow current (#5041) and temperature (#5042) records from western mooring. Current components and potential temperature are plotted vs. time. The direction components have been "rotated" to the right as shown to align N-S with outflow - inflow. The amount of rotation was changed at the 5 January point in the record to conform with the pronounced change in the current pattern as seen in Figure 3.

- A) Curves are constructed from hourly averages.
- B) Curves are constructed from the same data as above after being "low passed filtered" (see text).

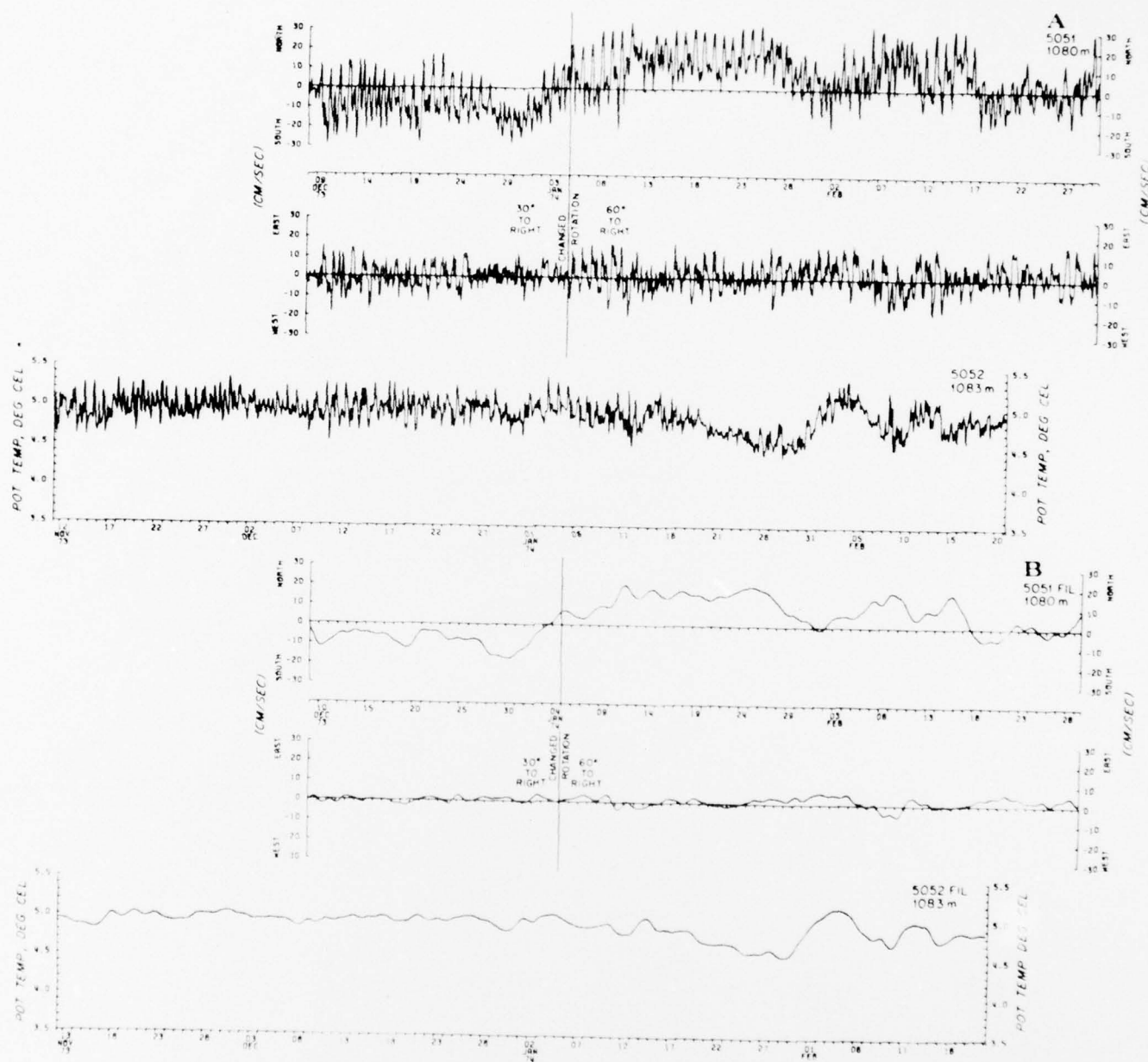


FIGURE 7 Shallow current (#5051) and temperature (#5052) records from eastern mooring. Details as in Figure 6. The temperature record was adjusted by  $-0.25^{\circ}\text{C}$  to compensate for an instrument calibration error.

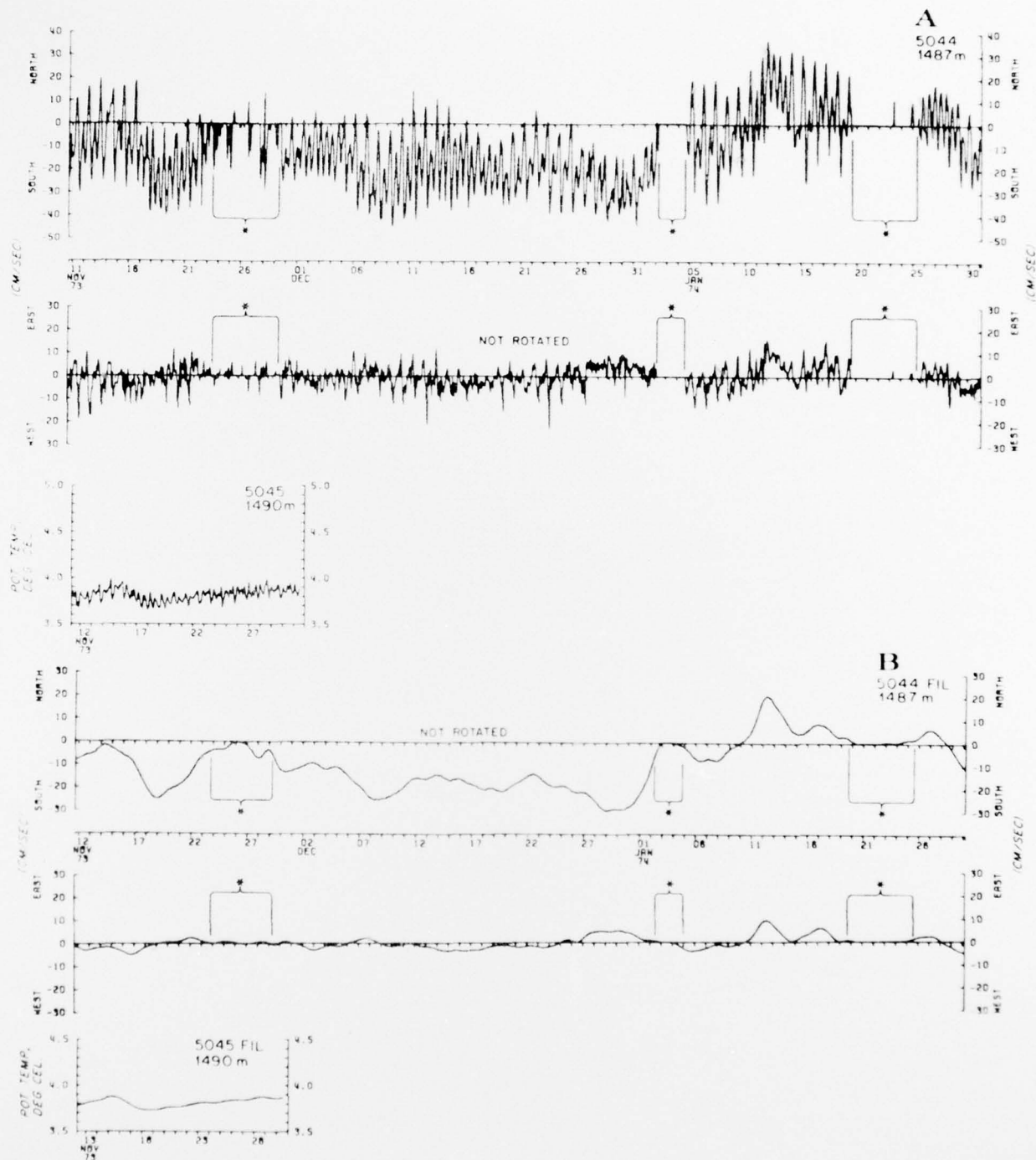


FIGURE 8 Deep current (#5044) and temperature (#5045) records from western mooring. Details as in Figure 6 except that no "rotation" of direction was carried out. \*Brackets indicate portions of the record where the current meter was undergoing intermittent periods of malfunctioning.

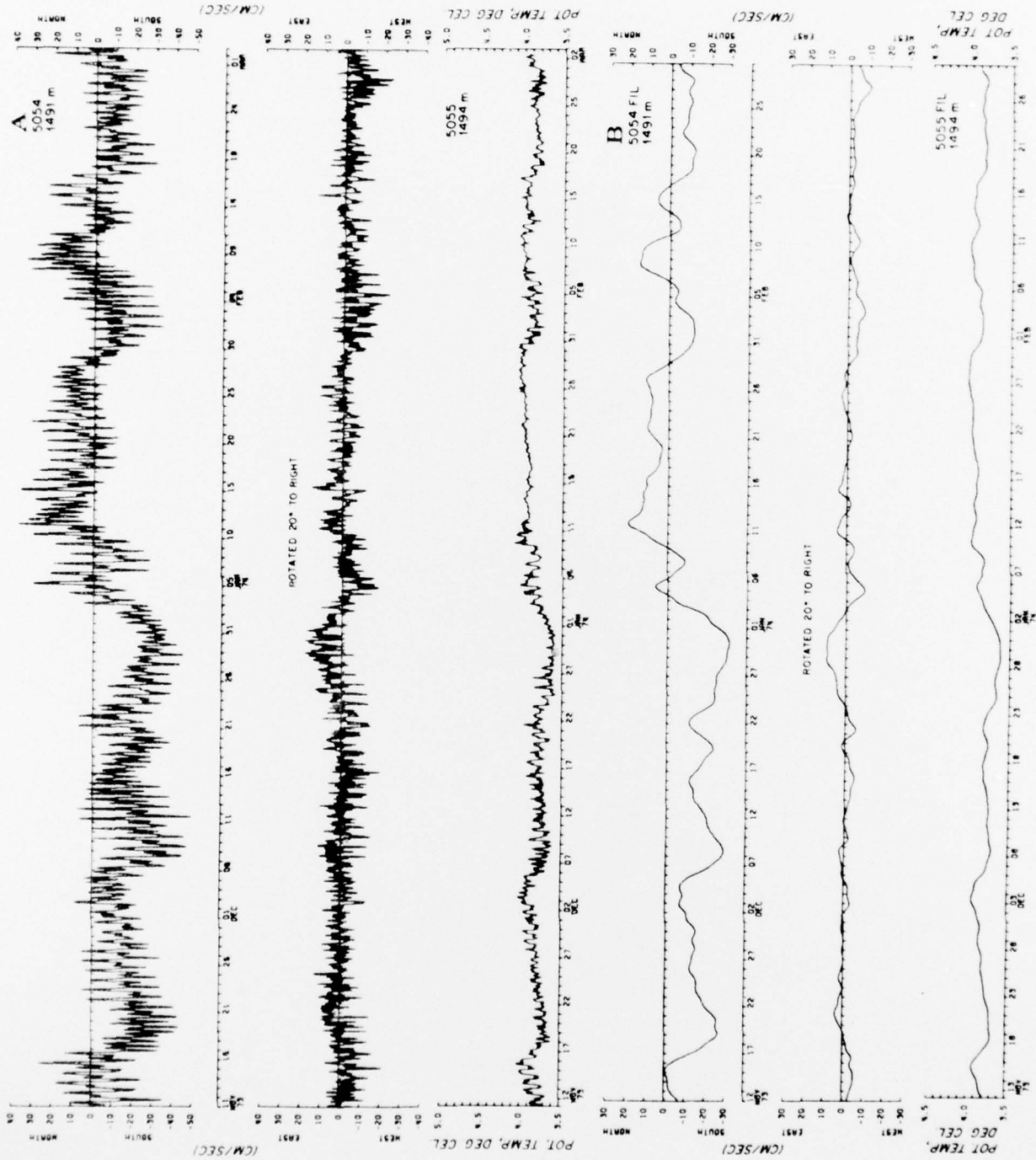


FIGURE 9 Deep current (#5054) and temperature (#5055) records from eastern mooring. Details as in Figure 6 except that the "rotation" was constant throughout.



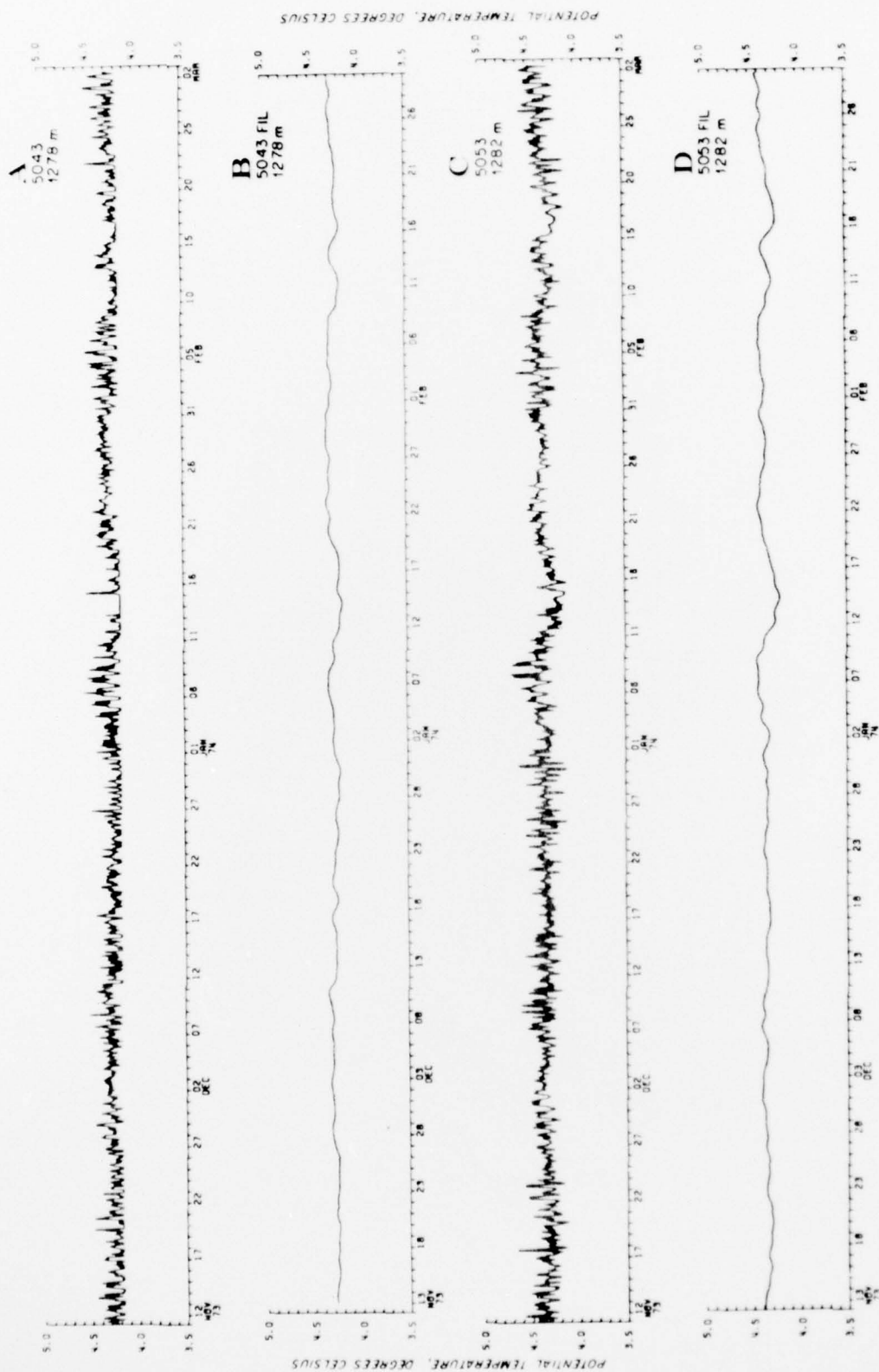


FIGURE 10 Intermediate temperature records plotted vs time. Record #5043, did not register below about 4.18° C due to an improper setting.

- A) Record #5043, western mooring, hourly average.  
B) Same, with "low pass filtered" data (see text).  
C) Record #5053, eastern mooring, hourly averages.  
D) Same, with "low pass filtered" data.

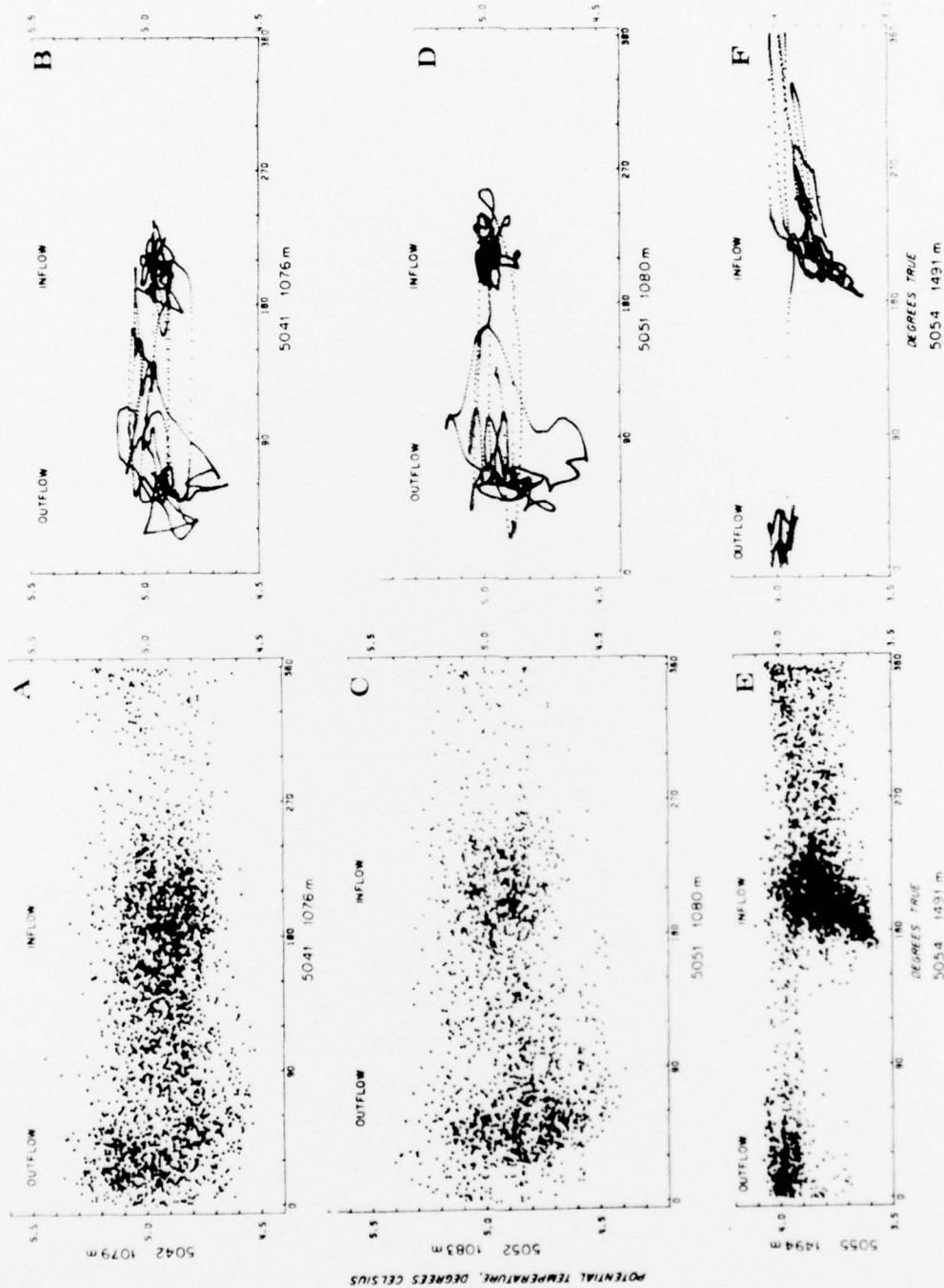


FIGURE 11 Potential temperature vs. direction of flow. Inflow and outflow directions are indicated by the heavy concentrations of dots.

- A) #5041 vs. #5042, western shallow instruments, hourly averages.
- B) As above except data have been "filtered".
- C) #5051 vs. #5052, eastern shallow instruments, hourly averages.
- D) As above except data have been "filtered".
- E) #5054 vs. #5055, eastern deep instruments, hourly averages.
- F) As above except data have been "filtered".

(Note: the western deep instruments have not been compared due to the very short record from the temperature recorder, #5045.)

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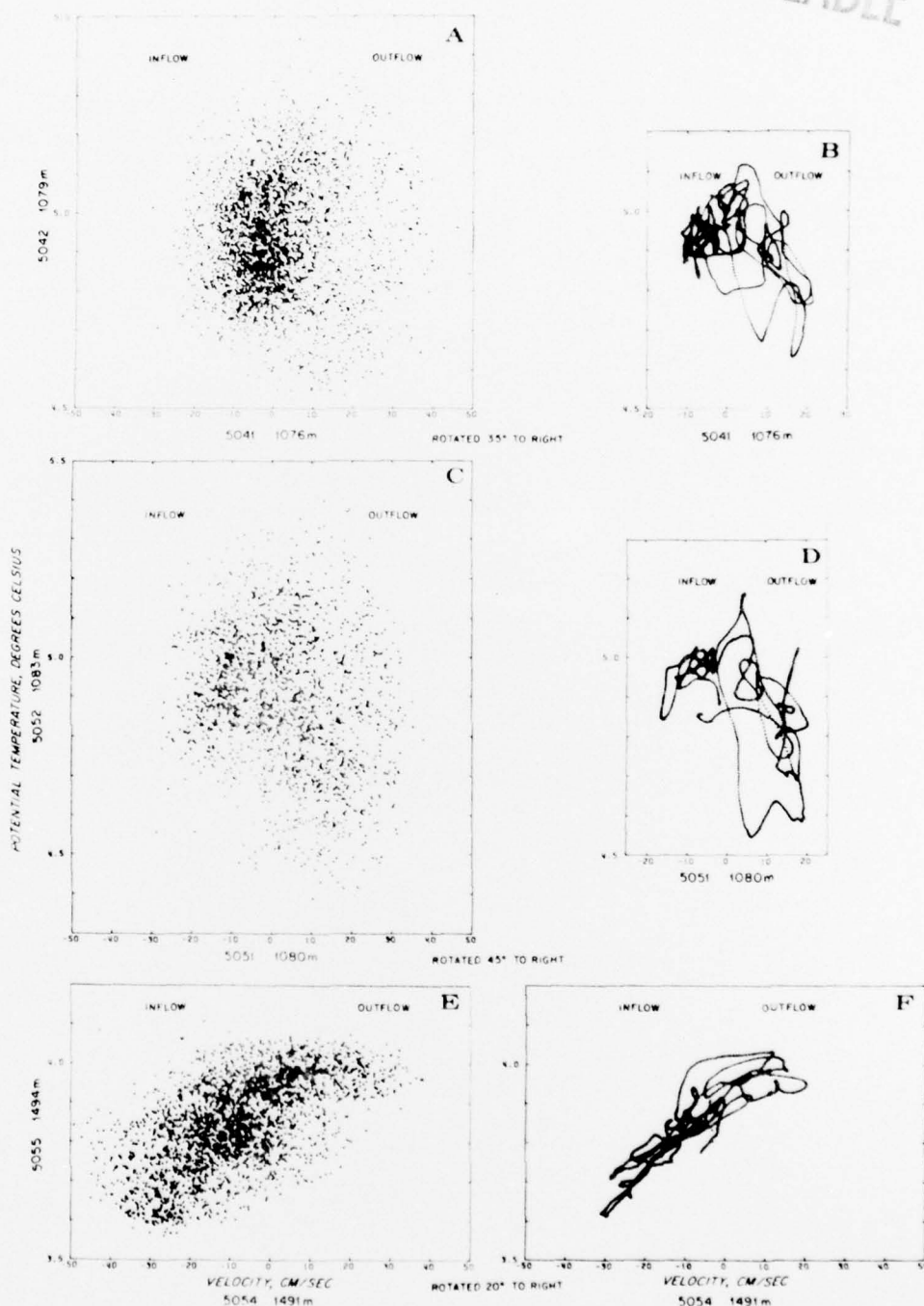


FIGURE 12 Potential temperature vs. outflow-inflow (N-S) components of flow. Outflow (N) is represented by positive velocities; inflow (S) by negative. The axis in each case has been rotated as indicated to align it with the mean axis of flow.

- A) #5041 vs. #5042, western shallow instruments, hourly averages.
- B) Same except for "filtered" data.
- C) #5051 vs. #5052, eastern shallow instruments, hourly averages.
- D) Same except for "filtered" data.
- E) #5054 vs. #5055, eastern deep instruments, hourly averages.
- F) Same except for "filtered" data.

(Note: the western deep instruments have not been compared due to the very short record from the temperature recorder, #5045.)

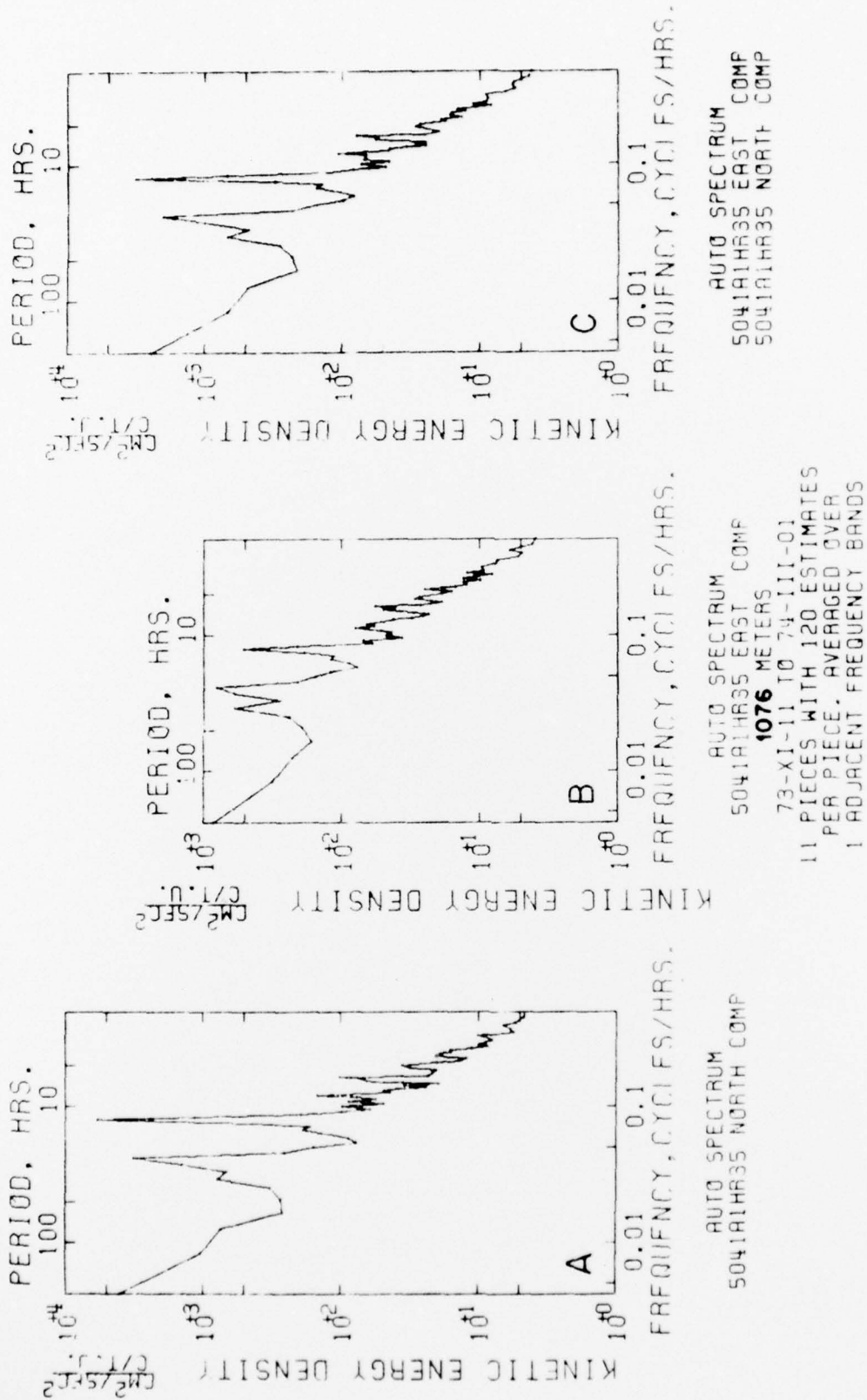


FIGURE 13 Energy spectra for current meter #5041, western shallow instrument. The current components have been rotated 35° to the right to align, N-S with the mean axis of the flow.

- A) North-south component.
- B) East-west component.
- C) North-south and east-west components combined.

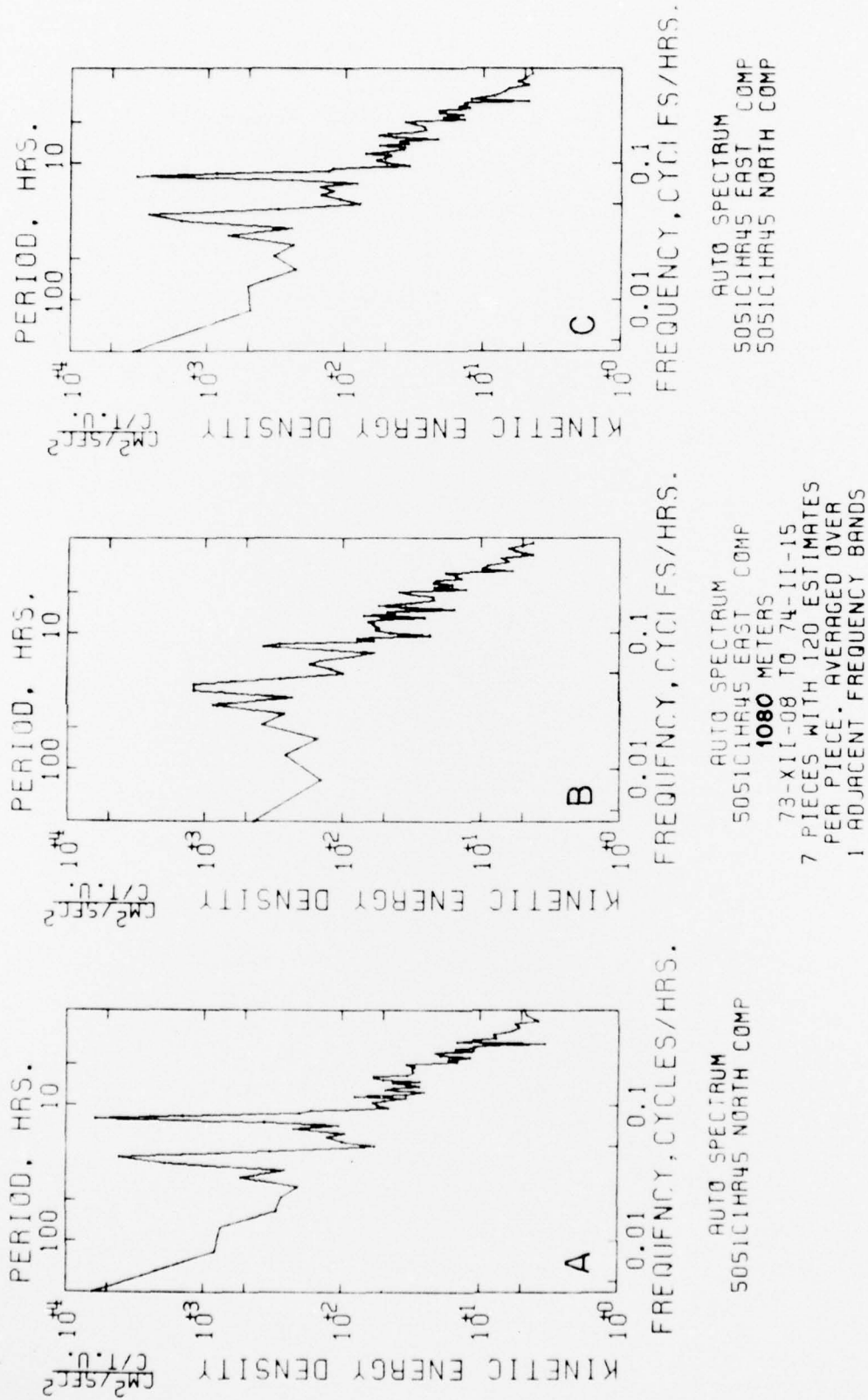


FIGURE 14 Energy spectra for current meter #5051, eastern shallow instrument. The current components have been rotated  $45^\circ$  to the right to align N-S with the mean axis of the flow.

- A) North-south component.
- B) East-west component.
- C) North-south and east-west components combined.



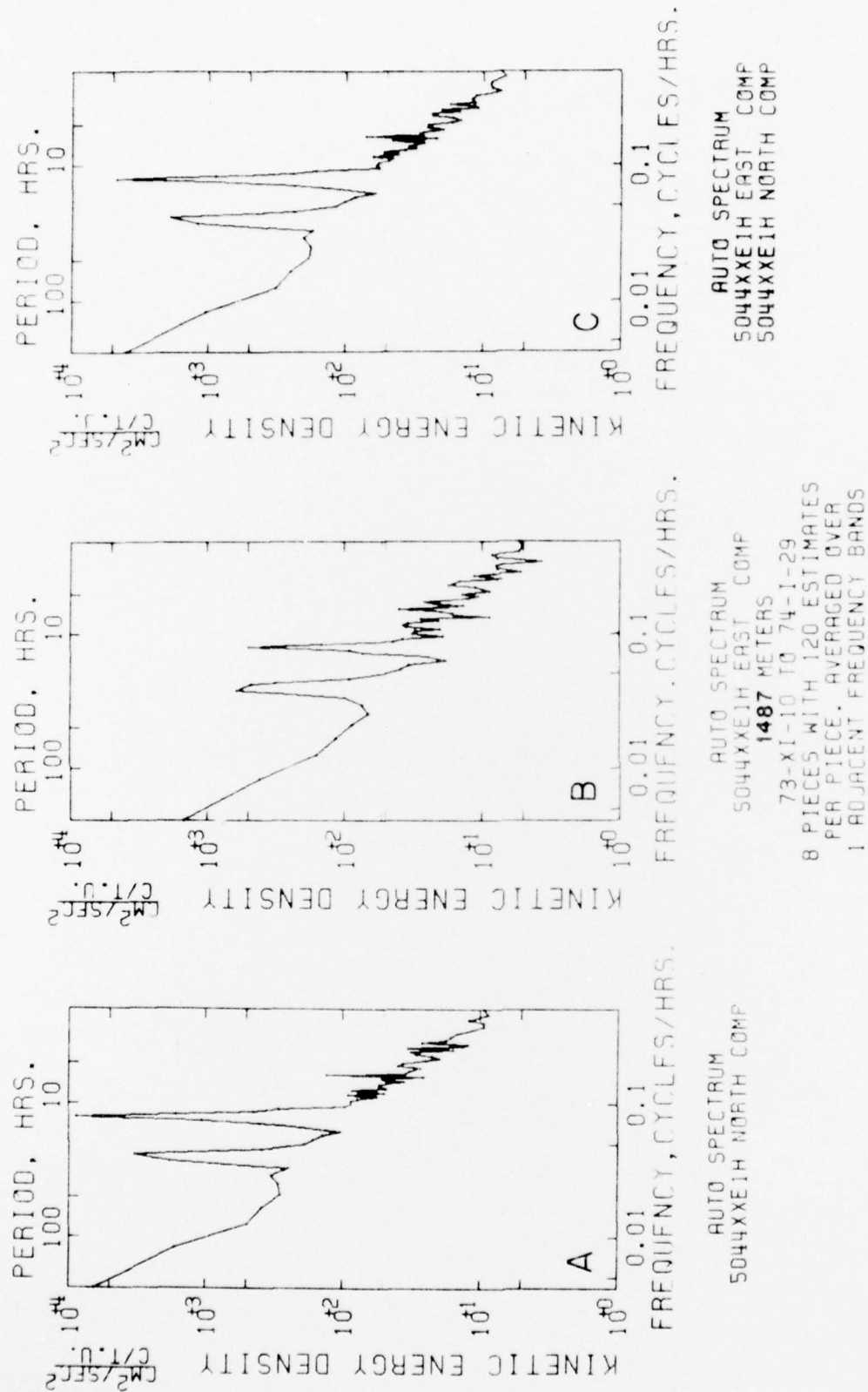


FIGURE 15 Energy spectra for current meter #5044, western deep instrument. No directional rotation was necessary to align N-S with the mean axis of the flow.

- A) North-south component.
- B) East-west component.
- C) North-south and east-west components combined.

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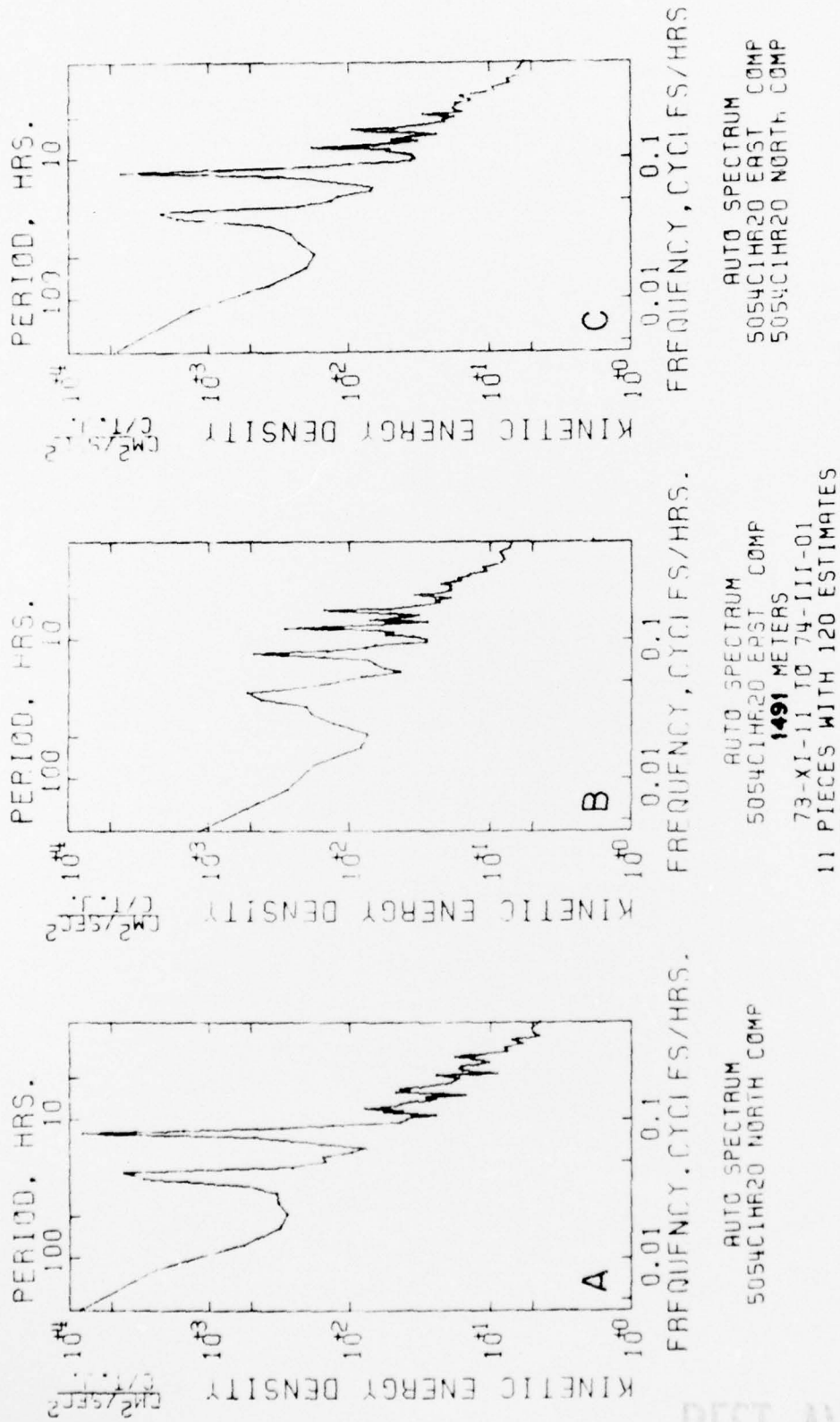


FIGURE 16 Energy spectra for current meter #5054, eastern deep instrument. The current components have been rotated  $20^\circ$  to the right to align N-S with the mean axis of the flow.

- A) North-south component.
- B) East-west component.
- C) North-south and east-west components combined.

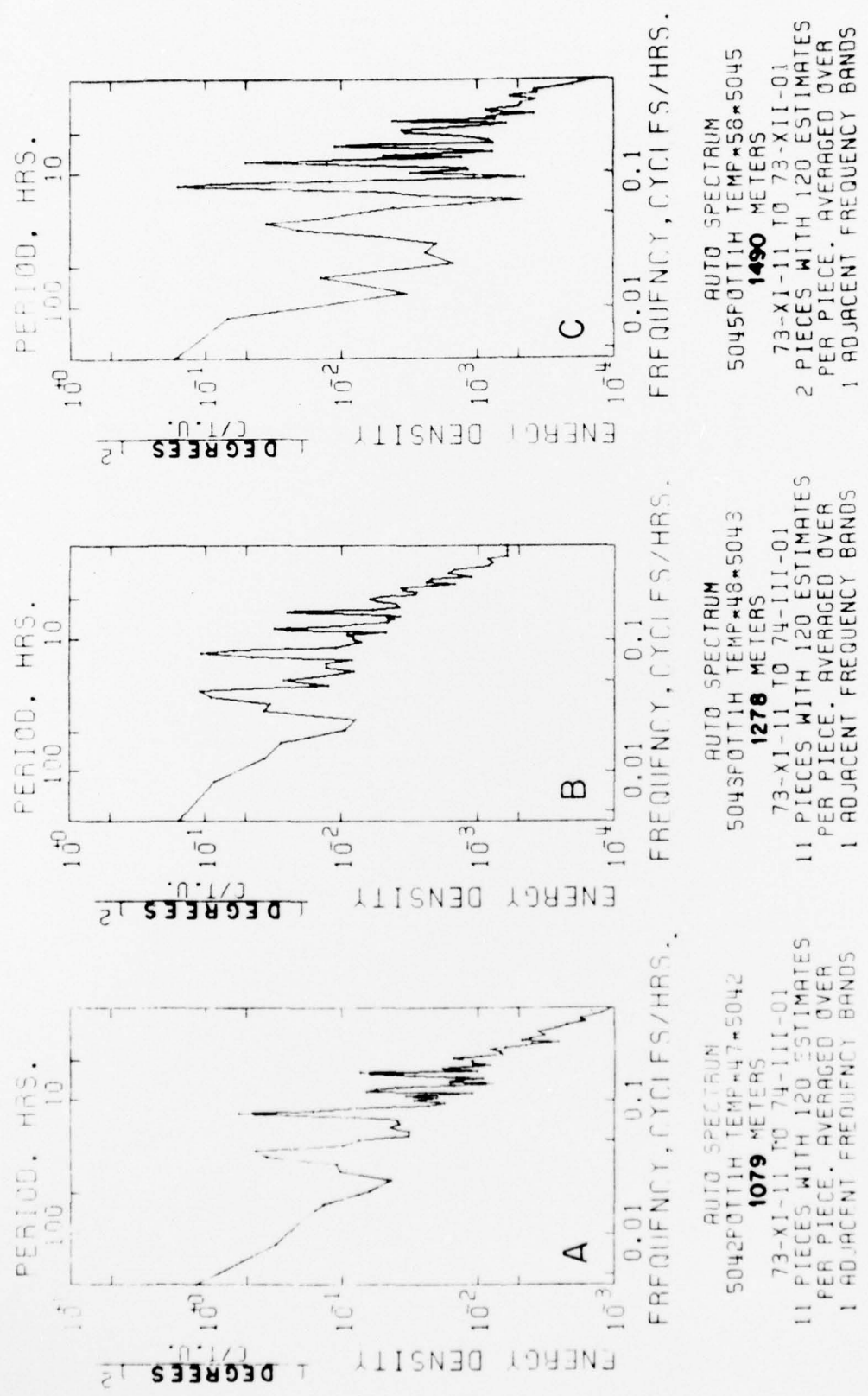


FIGURE 17 Temperature record energy spectra, western mooring.

- A) Shallow temperature recorder #5042.
- B) Intermediate temperature recorder #5043.
- C) Deep temperature recorder #5045.

The shallow and deep instruments were paired with current meters whose energy spectra are shown in Figures 13 and 15 respectively.

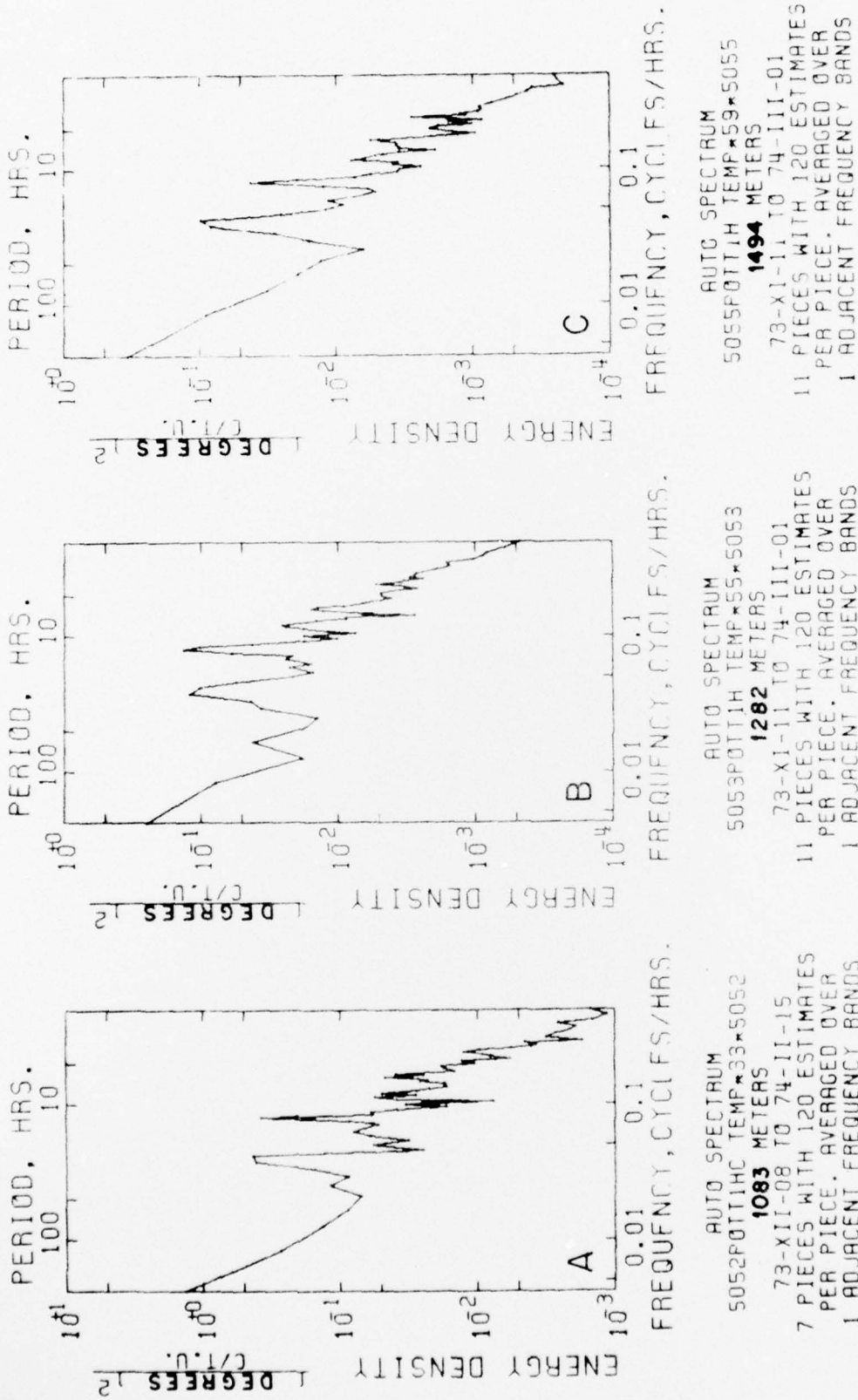


FIGURE 18 Temperature record energy spectra, eastern mooring.

- A) Shallow temperature recorder #5052.
- B) Intermediate temperature recorder #5053.
- C) Deep temperature recorder #5055.

The shallow and deep instruments were paired with current meters whose energy spectra are shown in Figures 14 and 16 respectively.

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