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An example of long-term variability for subsurface current and hydrographic patterns in the western North Atlantic

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ABSTRACT

An example of long-term variability along 55W, perhaps interannual, for current and temperature distributions during mid-1975-1977 is presented. The existence of significant energy in the 55W data set at time scales longer than mesoscale (50-150 days) has been clear for some time, but this is a first description of the latitudinal and vertical configuration of this low-frequency variability. The overall pattern observed may be described as a partial meander or lateral shift, associated with substantial changes in water mass properties. Perhaps we have identified a contraction of the subtropical gyre. Specific elements of the observed pattern include southward shifts and variations in intensity of abyssal currents, changes in the amount of vertical shear across the thermocline south of the Gulf Stream, along with southward shifts in current patterns at a variety of depths. The observed current variations are consistent with observed temperature changes from both moored instruments and hydrographic sections. There are also changes in the distribution of salinity anomaly, but these do not seem to be simply related to the changes in current and temperature patterns.

1. Introduction

Recent long-term observations are used to describe some characteristics of the variability in current, temperature, and water mass patterns along 55W from year to year (nominal, actually between averages over three moored array settings of roughly nine-month duration and between hydrographic sections made on deployment/retrieval cruises). The frequency distributions for the current fluctuations in the region of interest have been previously described by Schmitz (1978) and Schmitz and Holland (1982). The term secular scale (longest term variability) has been used for fluctuations with periods longer than roughly 50-150 days, the latter temporal range being referred to as the mesoscale. It has been clear for some time that the kinetic energy associated with the secular scale (as well as mesoscale) variability increases approaching the recirculation and the Gulf Stream from the interior of the subtropical gyre (Schmitz, 1978). However, horizontal and vertical patterns of this variability have not previously been established.

A spatial configuration for the secular scale variability along 55W that is con-

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sistent between both hydrographic observations and long-term moored instrument data has been identified. Latitudinal shifts of current and temperature patterns as well as variations in flow intensity and sign were observed, along with changes in vertical shear, local horizontal temperature gradient and water mass properties, but no significant change in net baroclinic transport. This fluctuation could be described as a partial (south) meander, or gyre contraction, associated with enhancement of the Eighteen Degree Water thermostad and a strong redistribution of salinity anomaly. Consistent with the sparse data base, we demonstrate the existence and configuration of the fluctuation qualitatively, appealing to visual differences between various graphical presentations of observational results.

2. Data and discussion

The data base along 55W consists of two-year (nominal) time series from moored instruments along with hydrographic sections from two cruises. Characteristics of the hydrographic data base have been described and discussed previously by McCartney (1980), McCartney *et al.* (1978), McCartney *et al.* (1980), and Schmitz (1980.) The moored instrument data base, obtained from POLYMODE Arrays 1 and 2 (hereafter PM1 and PM2), primarily the latter, has been described and discussed previously by Schmitz (1977, 1978, 1980) and Schmitz and Holland (1982).

Hydrographic sections were made along 55W on the last two cruises on which PM2 was handled, *Knorr* 60 in October 1976 and *Knorr* 66, June-July 1977. Each cruise involved 29 stations using Nansen bottles between moorings, along with CTD (conductivity-temperature-depth) stations at the mooring sites. The CTD data for *Knorr* 66 was of high quality, with the use of a 24-bottle rosette sampler and at some stations the addition of Nansen casts with 16 bottles. The *Knorr* 60 CTD data are of lower quality and are used only as described by McCartney *et al.* (1980). Water samples were processed for salinity, oxygen, and silicate.

PM1 was deployed for nine months; July-August, 1974 to April-May, 1975. Current-temperature meters located at 500, 1000, 1500 and 4000 m depths (nominal) at 3 sites in the vicinity of 28N, 55W are used here to characterize the relatively low energy interior of the North Atlantic. PM2 was in place from April-May 1975 to June-July 1977, deployed three times for seven to nine months each, with the variation in setting lengths depending on the details of ship scheduling. Current-temperature meters (some of which also had pressure sensors) were located at 600, 1000, 1500, and 4000 m depths from 31.5N to 37.5N along 55W, with meters deployed at 4000 m on four moorings from 38.5 to 41.5N (a few other moorings, not used here, were deployed at other longitudes but in the vicinity of 55W). Several moorings contained temperature-pressure gauges at a variety of depths, with 800 m (nominal) being standard. No attempt was made to set instruments above 4000 m in the immediate vicinity of the Gulf Stream, for technical reasons. Details have been reported by Spencer *et al.* (1979), Tarbell *et al.* (1978), and Bradley (1981).

We first discuss (*a*) the general characteristics of the hydrographic and moored instrument data and their relationship. Our purpose is to identify what is known about the nature of the flow regimes of interest. Then (*b*), the longer-term changes in each data set are described and intercompared. Our purpose is to identify spatial patterns for the lowest frequency variability.

a. General properties of the data base. The temporal mean (or averaged) hydrographic characteristics along 55W cannot be defined in the same way as for the moored instrument observations due to the sparseness of the data base. However, one can identify several persistent features. Temperature sections for each *Knorr* cruise are shown in Figure 1a, and corresponding distributions of salinity and silicate anomalies in Figure 1b. The western North Atlantic standard potential temperature-salinity and potential temperature-silicate relationships have been used to compute these anomalies [see McCartney *et al.* (1980) for a discussion of method, and Armi and Bray (1982) for a computation algorithm for salinity anomaly].

The thermocline or upper level signature of the Gulf Stream, a sharp horizontal temperature gradient (front), is clearly present in both *Knorr* 60 and 66 (Fig. 1a). This is the most prominent hydrographic characteristic, indeed the hydrographic definition, of the Gulf Stream (at any longitude). The intensity of the front, or horizontal temperature gradient, or vertical shear for the Gulf Stream, weakens going downstream from the longitude of Bermuda (Worthington, 1976). The axis of the Stream, defined as the location of the 15° isotherm at 200 m depth, is at approximately 41N on *Knorr* 60 and 39N on *Knorr* 66. This characteristic is known to change position on a variety of time scales, although the spectrum is not sharply defined at 55W [the most substantial data base on Stream position, and associated detailed analysis thereof (Halliwell and Mooers, 1979), are geographically constrained west of 65W]. Time averages of the location of the Stream axis based on mechanical BT data (Schroeder, 1963) indicate a mean latitude of approximately 40.5 at 55W. Frequency distributions for all so-called ocean station data (less than 20 are available for the area of interest) on file at the U.S. National Oceanographic Data Center yield a "mean" axis of about 39N at 55W (Fisher, 1977).

The offshore (~ southern) edge of the eastward vertical shear associated with the Stream, defined to be the dynamically highest station, occurs at 39N for *Knorr* 60 and 37.5N for *Knorr* 66. Time averages of all XBT data on file yield 37N as the mean position at 450 m depth of the offshore edge of the eastward vertical shear associated with the Gulf Stream at 55W (Richardson, 1980).

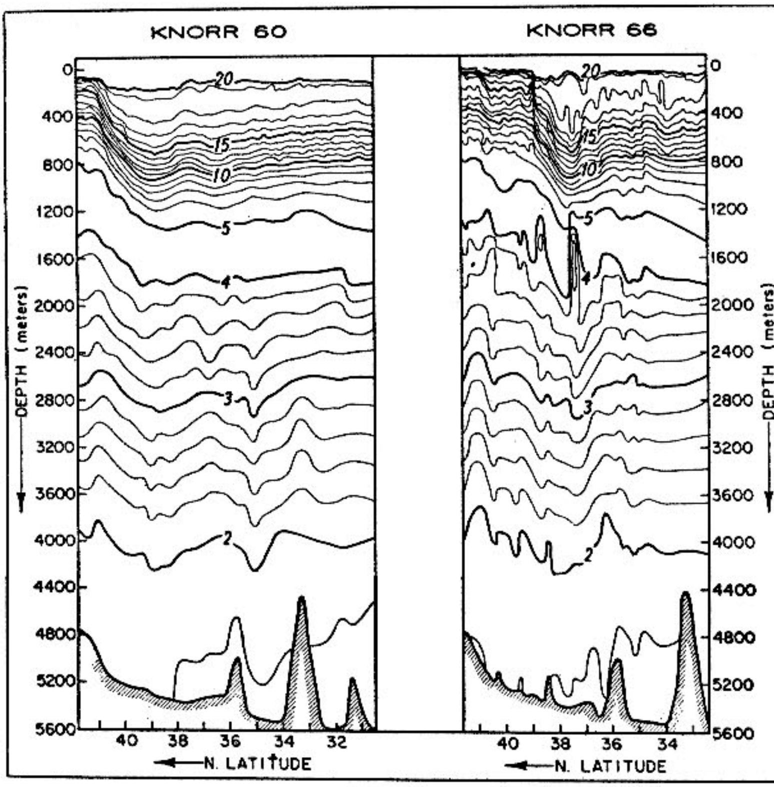


Figure 1. (a) Temperature sections for *Knorr* 60 and *Knorr* 66. Adapted from Figure 3 by McCartney *et al.* (1980). The *Knorr* 60 section contains data from hydrographic stations and 750 m XBTs and the *Knorr* 66 section data from CTD casts, hydrographic stations and 750 m XBTs.

Richardson (1980, Fig. 3) also finds 39N as the mean latitude of the largest latitudinal temperature gradient at 450 m depth.

Weaker and opposite sloping isotherms are present offshore of the Stream on both *Knorr* 60 and 66 (Fig. 1a); the hydrographic signal of the recirculation-return flow regime (at any longitude). The width of the region of horizontal temperature gradient or vertical shear taken to be the hydrographic definition of the recirculation-return flow region was 600-700 km for *Knorr* 60 and 150 km for *Knorr* 66 (McCartney *et al.,* 1980). This area, along with the offshore segment of the Gulf Stream, is the formation and principal (by volume) residence region for Eighteen Degree Water, which also spreads out over a larger area in the North Atlantic (Worthington, 1976). The property that characterizes this water mass is the low magnitude of the vertical temperature gradient near 18°C, a thermostad. The Eighteen Degree Water thermostad is present in the data sets for both *Knorr* cruises under examination, with temporal variation as described in the following.

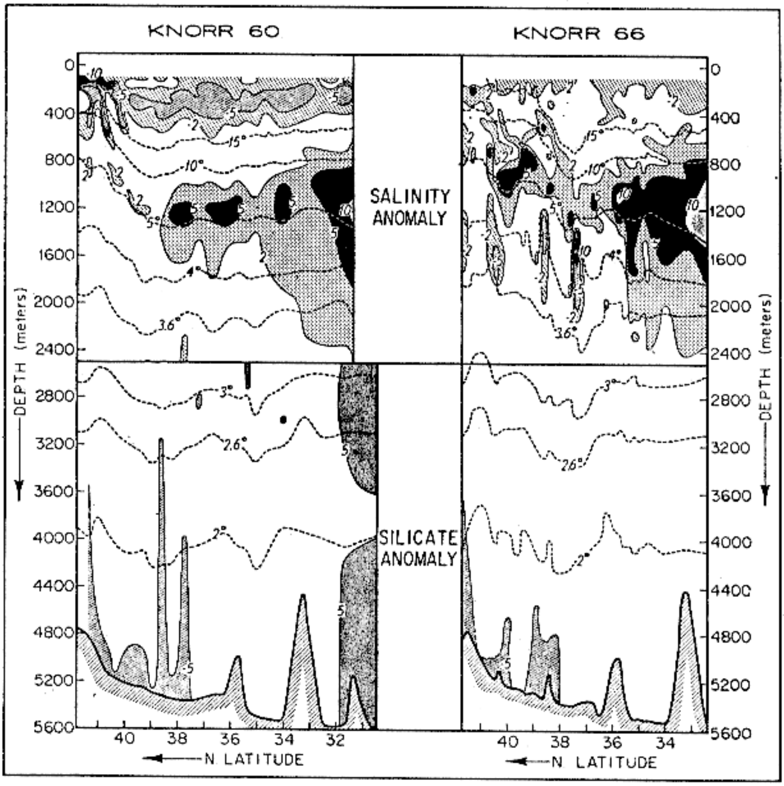


Figure 1. (b) Selected isotherm depth contours from Figure 1a, with salinity and silicate anomaly contours superimposed, constructed from *Knorr* 60 hydrographic stations and *Knorr* 66 hydrographic stations and CTDs. Salinity anomaly (hundredths of a part per thousand) contours are shown at depths above 2500 m (denoted by a solid line) and silicate anomaly contours (microgram atoms per liter) below. Largest anomalies are shaded darkest. Adapted from Figure 4 by McCartney *et al.* (1980).

The co-existence (Fig. 1b) of positive salinity anomalies—indicative of the influence of Mediterranean water—with the subtropical gyre recirculation (and even the Gulf Stream) may seem surprising in light of Worthington's (1976) stated requirement of closing the recirculation north of the Mediterranean tongue. However, Worthington's (1976) Gulf Stream System closes at 40W along 36N, at a positive salinity anomaly level bounded by roughly 10. East of 40W, this anomaly rises dramatically. Comparison of Worthington's charts of salinity on temperature surfaces in the thermocline with his circulation maps shows a range of salinity associated with the Gulf Stream—recirculation system that easily accommodates a positive salinity anomaly level of 5-10, as observed and shown in Figure 1b. It is the much higher salinity anomaly regions farther south and east that Worthington's circulation is arranged to avoid.

The currents obtained from moored instrument observations along 55W have been described in terms of the longest temporal averages available by Schmitz (1980). The mean zonal components north of 30N in Figure 1c are two-year averages (nominal) for the PM2 data. The horizontal vectors in Figure 1d are similar averages (at latitudes north of 30N). At 28N, means for three nine-month duration (nominal) PM1 moorings are shown on Figure 1d as an indication of the relatively weak currents there. Starting from north to south, the time-averaged velocities in Figure 1c and 1d can be taken to represent the existence of the following four mean flow regimes: (a) A mean westward flow at 4000 m depth centered at 40.5N. This time-averaged flow is under the quasi-synoptic Stream axis for *Knorr* 60, 1.5° to the north of the axis for *Knorr* 66, under the climatological axis position according to Schroeder (1963), and centered 1.5° north of the climatological position reported by Fisher (1977) and Richardson (1980). Westward mean flow has also been observed at 40.5N by Hendry (1982) at longitudes near but not precisely at 55W. Westward mean flow under (estimates of) the climatological position of the axis of the Gulf Stream was also found at 70W by Schmitz (1977). It will be seen in the following that this flow is present for each array setting along 55W, although slightly weakening in intensity over the total two-year period of observation; (b) A weakly depth-dependent eastward mean flow centered around 37.5N. This is south of the offshore edge of the Stream for *Knorr* 60, under it for *Knorr* 66, and .5° north of the mean position of the edge based on the Richardson (1980) data. Eastward mean flow is also present at a similar position relative to the climatological axis in the abyssal moored instrument data along 70W (Schmitz, 1977). The relationship of this time-averaged flow pattern to the current structure of the hydrographic-synoptic Gulf Stream has not been established, although it is known that the offshore segment of the Stream is one of comparatively weak vertical shear. Eastward flow near 37.5N is present for each array setting, but its vertical structure changes; (c) A weakly depth-dependent mean flow to the west centered near 36N in Figure 1c and 1d, called the recirculation. The location and structure of this flow regime may vary significantly with longitude. Westward mean flow near 36N is present for each array setting, but its vertical structure changes; (d) A weaker time-averaged westward flow in the thermocline south of 35N. This is the return flow. Note that the abyssal mean flow in this regime is to the east, although very weak. In this flow regime, zonal current components change sign for different array settings.

The relationship between the moored instrument mean currents with salinity and silicate anomalies is relatively straightforward in general terms. Salinity and silicate anomaly contours for *Knorr* 60 are superimposed on Figure 1c and those for *Knorr* 66 on Figure 1d. These contours are a selected subset from Figure 1b. The Stream axis and offshore edge indicators in Figures 1c and 1d are those observed on either *Knorr* 60 or 66. We realize that in Figures 1c and 1d we

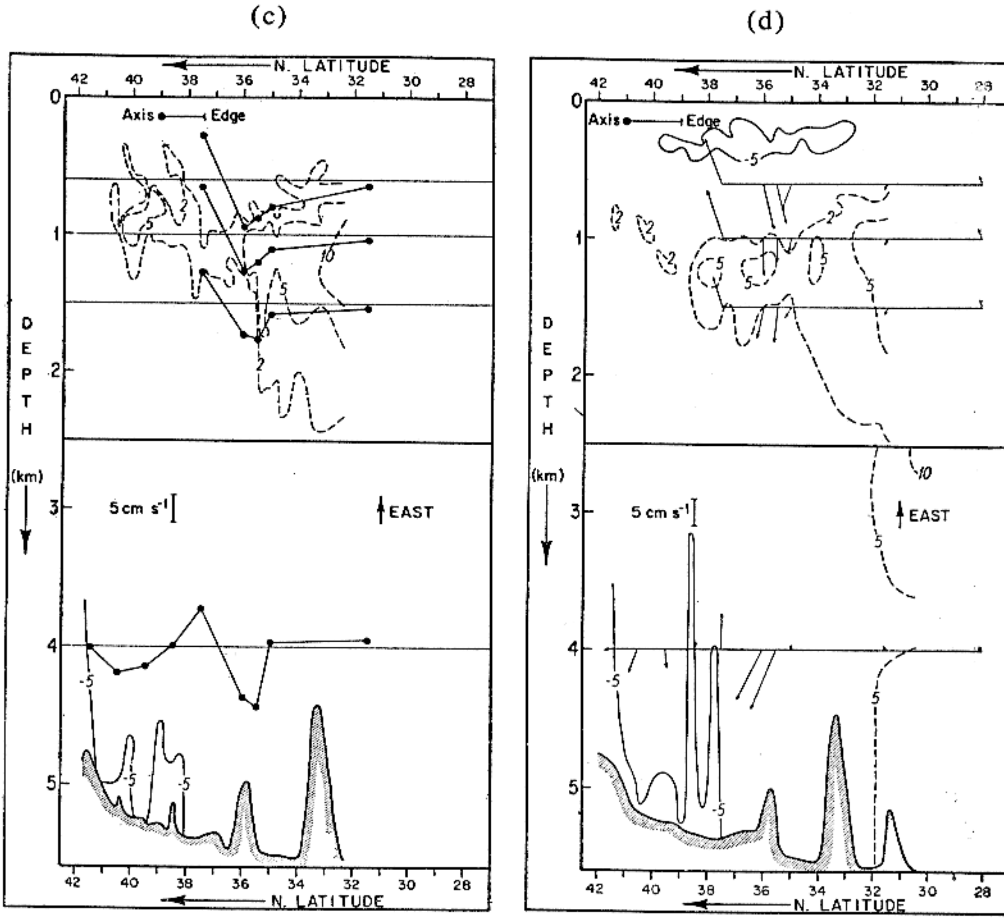


Figure 1. (c) Mean (two-year, nominal) zonal current components along 55W superimposed on a latitude-depth section of selected salinity and silicate anomaly contours from *Knorr* 66. Salinity anomaly contours are shown above 2500 m depth (denoted by a heavy solid line) and silicate anomalies below. Negative anomaly contour lines are solid, positive dashed. The zeros (denoted by a light solid line) of the mean zonal currents are at the depths (nominal) of the four standard levels for the moored instruments, with orientation and scale as indicated in the center of the figure. The dot labeled axis indicates the location of the 15° isotherm at 200 m for *Knorr* 66, with the bracket labeled Edge located at the southern end of the hydrographic Gulf Stream. (d) Mean (two-year, nominal) horizontal current vectors along 55W superimposed on a latitude-depth section of selected salinity and silicate anomaly contours from *Knorr* 60. Partially adapted from Figure 9 by Schmitz (1980). Salinity anomaly contours are shown above 2500 m depth (denoted by a heavy solid line) and silicate anomalies below. Negative anomaly contour lines are solid, positive dashed. The zeros (denoted by a light solid line) of the mean zonal currents are at the depths (nominal) of the four standard levels for the moored instruments, with orientation and scale as indicated in the center of the figure. The dot labeled axis indicates the location of the 15° isotherm at 200 m for *Knorr* 60, with the bracket labeled Edge located at the southern end of the hydrographic Gulf Stream.

are comparing two-year means with quasi-synoptic sections, but in so doing we are interested in the persistent properties of the salinity anomaly field. The relative time scales are unknown but it may be that the gross features of synoptic salinity anomaly distributions are indicative of longer time scale adjustments.

The hypothesis of a latitudinally restricted recirculation by Worthington (1976), based on distributions like those in Figures 1a and 1b, is clearly supported by the moored instrument data in Figures 1c and 1d, most noticeably at abyssal depths where there is a transition from a relatively strong and narrow recirculation to a weak flow of opposite sign at quite high latitude (~ 35N). Note, however, that some of the salinity anomaly contours associated with Mediterranean water are imbedded in both the recirculation and the weakly depth-dependent eastward flow immediately to the north of it in Figures 1c and 1d. These anomalies, as noted above, are also consistent with Worthington's (1976) deep subtropical gyre boundary at 36N, 40W. On the other hand, the existence of positive salinity anomalies of 5 to 10 in the recirculation and Gulf Stream along 55W, when contrasted with the lack of observation of positive anomalies of this magnitude in the recirculation regime west and north of Bermuda, has been taken by Schmitz (1980) to suggest the existence of a relatively small recirculating gyre near 55W on the southern edge of the Stream [also consistent with the temperature map prepared by Richardson (1980)].

b. Spatial patterns of the long-term variability. Although the differences in hydrographic data patterns for the two *Knorr* cruises under consideration could be associated with periods shorter than the interval between the cruises, we will first document the nature of the variations and then demonstrate that they are qualitatively consistent with fluctuations in averages over array setting durations for the moored instrument data. Changes between the two *Knorr* cruises in the latitudinal distribution of a thermocline-level and an abyssal-level isotherm are contained in Figure 2a, plotted using hydrographic station data only for simplicity in comparison. The latitudinal pattern for the 10° isotherm shifted south by about 1.3° of latitude over the nine months (nominal) between the two cruises. There was an increase in the local gradient(s) of the depth of this isotherm in the recirculation, although the net or regional depth variation across the southern part of the section did not change. The maximum depth of this surface was not different between the two cruises, although the maximum depths of shallower isotherms did increase. In fact, the geostrophic transports relative to the bottom are nearly identical; 89 and 90 $\times$ $10^6 m^3 s^{-1}$ for the Gulf Stream regime for *Knorr* 60 and 66 respectively, and similarly 58 and 60 $\times$ $10^6 m^3 s^{-1}$ for the recirculation-return flow region (McCartney *et al.*, 1980).

The period between the two cruises was one of intensification of the Eighteen Degree Water thermostad, both at longitudes to the west of 55W (Leetmaa, 1977) and at 55W (Fig. 2b). The stations plotted in Figure 2b are those with the maxi-

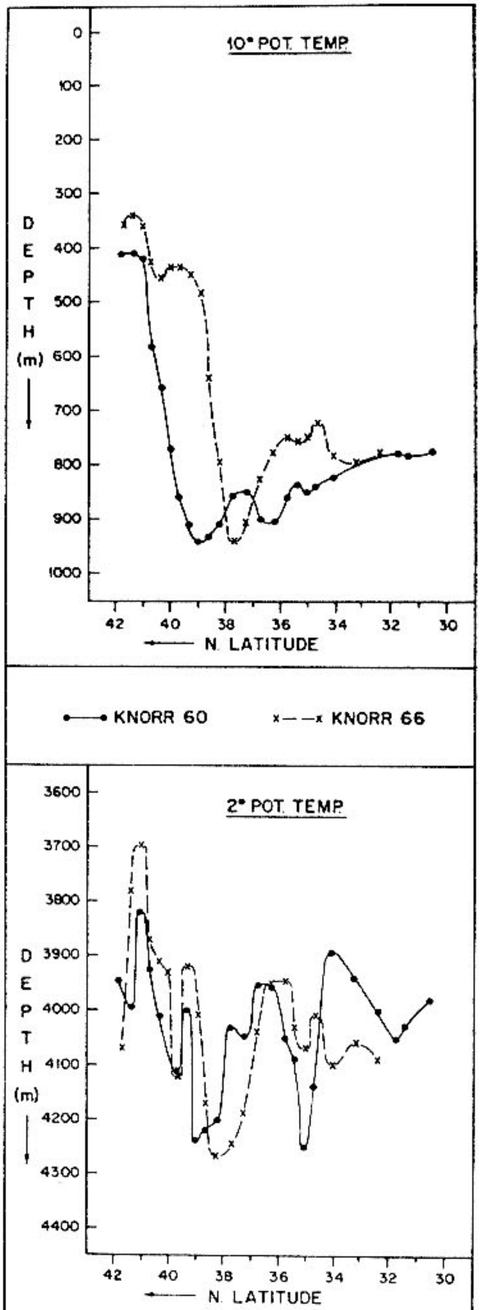
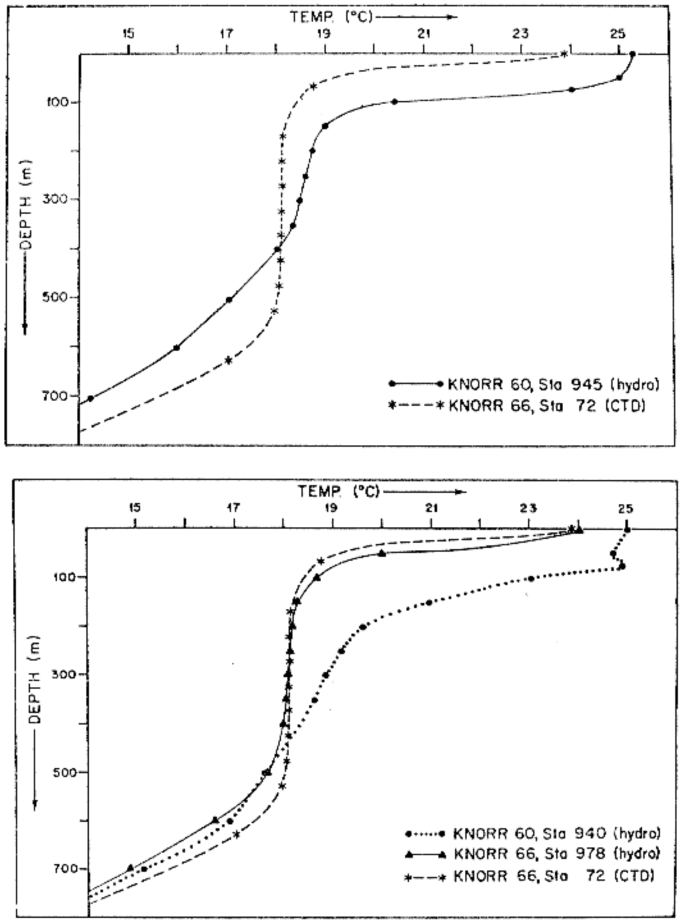


Figure 2. (a) Depths of indicated isotherms from *Knorr* 60 and *Knorr* 66.



(b)

(c)

Figure 2. (b) Temperature-depth plots for the stations from *Knorr* 60 and 66 with the maximum Eighteen Degree Water development. (c) Temperature-depth plots for the stations from *Knorr* 60 and 66 with the maximum thermocline (10° isotherm) depths.

mum (nominal) Eighteen Degree Water development, and the depths of the 10° isotherms differ by about 50 m. Temperature-depth profiles for the two stations identified by McCartney *et al.* (1980) as the dynamically highest for each cruise (station 940 and CTD 72) are plotted in Figure 2c, along with the hydrographic station in Figure 2a with the deepest 10° isotherm. The 10° isotherm depths for these stations all lie between 940 and 948 m.

Jenkins (1982) has identified salinity variations in Eighteen Degree Water that appear to be associated with temporal fluctuations in its renewal. Talley and Raymer (1982) also discuss the temporal fluctuations in Eighteen Degree Water characteristics, particularly from the point of view of its vertical homogeneity. They show sections of potential vorticity for the two *Knorr* cruises under consideration here that indicate an increase in potential density of the Eighteen Degree Water, and a decrease in its potential vorticity, indicative of enhanced vertical homogeneity associated with recent formation. The existence of an anomalously fresh lens of water in the relevant depth range on *Knorr* 66 (Fig. 1b), in contrast to its absence for *Knorr* 60, is also evidence for recently formed Eighteen Degree Water at 55W for *Knorr* 66.

The 2°C potential temperature level (Fig. 2a) is more highly structured spatially (latitudinally) than that for 10°C, and the southward shift of the central lobe of this pattern between cruises was about 1° of latitude. Some of this horizontal structure may be associated with bottom topography. One mechanism has been discussed by Owens and Hogg (1980): bottom trapped—vertical attenuation by stratification—Taylor columns. At abyssal levels one would expect more horizontal structure, mimicking the bottom topography.

The variability over the nine-month interval between *Knorr* 60 and 66 in latitudinal temperature sections suggests a southerly shift, or meander, or perhaps even a gyre contraction. The 10° isotherm in the Gulf Stream moves south without noticeable change in shape but there is considerable local variation in the structure of this isotherm in the recirculation-return flow regime. However, the changes between the two hydrographic sections could be associated with variability on time scales shorter than the interval between cruises. The moored instrument data are used to resolve this point. Changes in the zonal current pattern between each setting of PM2 are contained in Figure 3. Standard averages (seven to nine month) over the setting intervals are used to identify the longer periods in the moored instrument data and suppress the influence of the mesoscale eddy band (period range 50-150 days, nominal). The array setting averages are convenient to compare with hydrographic cruise data, particularly in light of the changes between *Knorr* 60 and 66. For the moored instrument time-averages in Figure 3, the axis and southerly or offshore edge of the Gulf Stream are characterized in a different way than that used when also presenting data from the hydrographic cruises. The axis is a span of latitudes (39.5 to 40.5N) from Schroeder (1963) and Fisher (1977), and the southern edge from Richardson (1980).

The abyssal eastward flow near 37.5N decreased in width by about 1° of latitude between averages over the first and second array settings (Fig. 3a), accompanied by a similar increase in width along with a reduction in intensity of the counterflow near the location of the climatological mean position of the axis of the Gulf Stream. The recirculation did not vary essentially in any property associated with regional structure and amplitude, although there is significant variability at the mooring site on its southern edge (~ 35N). The currents in the return flow regime changed sign at all depths.

The southward shift in average current pattern in the thermocline between the

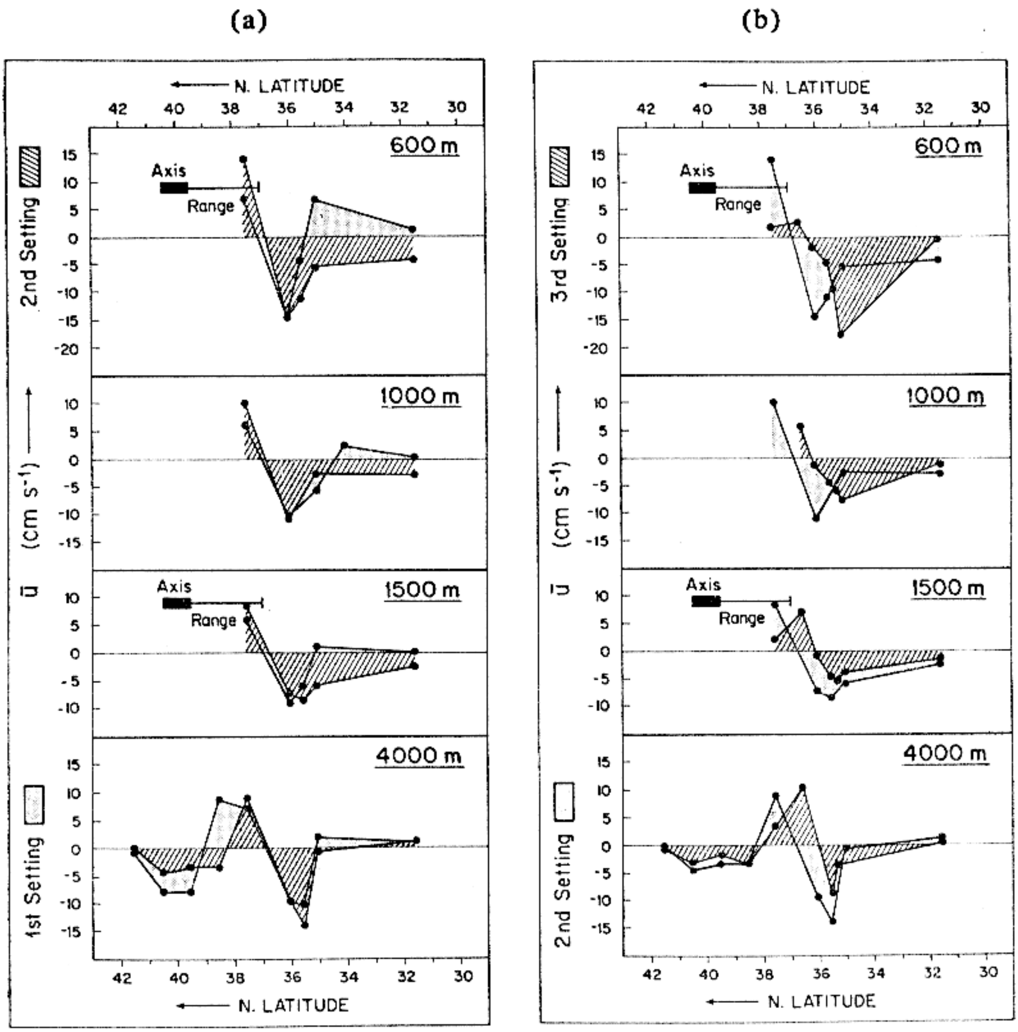
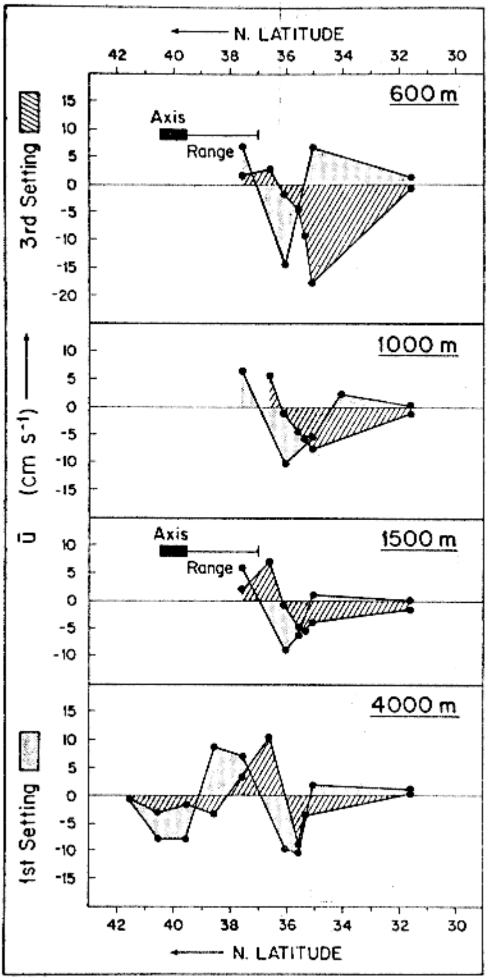


Figure 3. (a) Time-averaged zonal current components ($\bar{u}$) for PM2 array settings 1 and 2. The areas under the curves for all contributions to Figure 3 are shaded in order to enhance perception of differences. In all frames of Figure 3, the solid bar labeled axis indicates a span of positions for the climatological location of the 15° isotherm at 200 m according to Schroeder (1963) and Fisher (1977). The line and bracket labeled Range give an estimate of climatological variations in Stream domain, with the southerly bracket adapted from Figure 3 by Richardson (1980). (b) Time-averaged zonal current components ($\bar{u}$) for PM2 array settings 2 and 3.

second and third array settings (Fig. 3b) is 1 to 1.5° of latitude, in general agreement with the *Knorr* 60 and 66 data in Figure 2a. The overall latitudinal shift in zonal current pattern for the 18-month period between the mid-points of the first

(c)



(d)

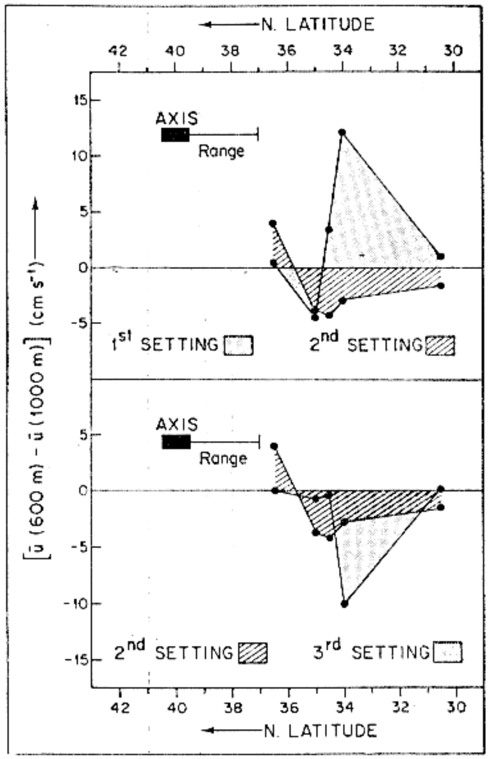


Figure 3. (c) Time-averaged zonal current components ($\bar{u}$) for PM2 array settings 1 and 3. (d) Time-averaged zonal current component ($\bar{u}$) differences between 600 and 1000 m depths for indicated PM2 array settings.

and third array settings (Fig. 3c) is determined by the last nine-month period in the upper 1500 m, but is more like 2°C at 4000 m depth for the eastward mean flow near 37.5N. The prominent visual changes in current structure occurred near the Gulf Stream and south of 35N between settings 1 and 2 and in the recirculation between settings 2 and 3. Both weakly depth-dependent flow regimes for settings 1 and 2 increase in vertical shear for setting 3 (the eastward regime becoming strongest with increasing depth, and the opposite for the recirculation).

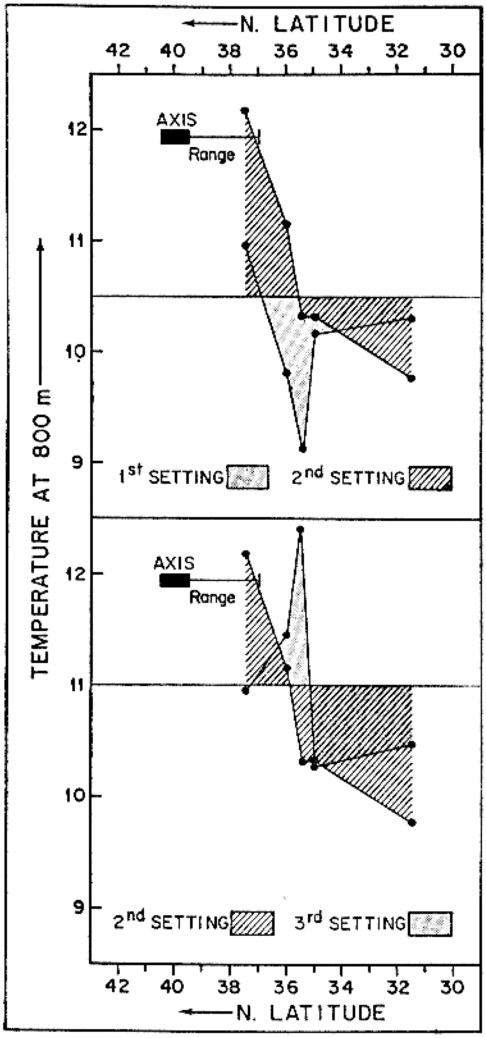


Figure 3. (e) Time-averaged 800 m temperatures for each PM2 array setting.

The change in vertical variation of the zonal current component in the main thermocline is brought out more explicitly by Figure 3d, where differences in zonal current components between 600 and 1000 m depths are plotted for each PM2 array setting. These changes in vertical shear (velocity difference) between settings 2 and 3 are qualitatively consistent with the 10° isotherm data from *Knorr* 60 and 66 in Figure 2a (see also Fig. 3e below). Velocity differences in the vertical are the maximum for PM2 settings 1 and 3 near 35N, on the southern edge of the recirculation, but are much smaller in the long-term mean (as indicated by Fig. 1c), because the vertical shears for setting 1 tend to cancel those for setting 3 (the largest amplitudes are of opposite sign).

The temperature fields for both hydrographic and moored instrument observations show qualitatively analogous structures and changes in pattern. Variations between time averages over the settings for the moored array temperature distribution at 800 m depth are contained in Figure 3e. Potential temperatures at 800 m depth for each of the two *Knorr* cruises are plotted in Figure 4a. The changes are consistent with those inferred from 10° potential isotherm depths in Figure 2a and moored instrument temperatures at 800 m in Figure 3e. 800 m temperatures from moored instrument and hydrographic data sets are compared in Figure 4b. The hydrographic data in Figure 4b are slightly smoothed versions of those in Figure 4a, and potential temperatures are used since there are no significant differences between them and temperatures at this depth. *Knorr* 60 results and averages for the second array setting nearly overlay. There are consistencies but also an offset and shift in comparing the *Knorr* 66 data and the averages for the third array setting. It may be that the temperature patterns shifted farther south between the two (pertinent) cruises than indicated by the *Knorr* 66 data.

The difference between the patterns of salinity anomaly on *Knorr* 60 and 66 are striking. The major changes were: (a) the strong upper-layer fresh anomaly on *Knorr* 60 has disappeared by the time of *Knorr* 66, indicating the presence of recently formed Eighteen Degree Water (the standard temperature-salinity curve was prepared during a period of relatively strong formation; see McCartney *et al.*, 1980); (b) anomalously salty Mediterranean water penetrates quite far to the north, definitely into the Gulf Stream and perhaps into slope water for *Knorr* 66, relative to the situation for *Knorr* 60, although even the *Knorr* 60 salinity anomalies are themselves located as far north as the recirculation or slightly beyond; (c) cells of negative salinity anomaly in the temperature range 3.5 to 4.5°C associated by McCartney *et al.* (1980) with water of Labrador Sea origin were observed on *Knorr* 66 but not *Knorr* 60.

Changes in the relationship between salinity anomaly and current patterns are shown in Figure 5. The salty anomaly associated with Mediterranean water is embedded in both eastward and westward flows in both frames of Figure 5, and these salinity anomaly/current distributions clearly do not imply a barrier to any flow pattern. The water having Mediterranean influence appears to be simply circulating in the gyre. This statement is true for each array setting and cruise in Figure 5. In *Knorr* 66, anomalously salty water has also clearly penetrated even farther north, into and perhaps beyond the intensely baroclinic segment of the Gulf Stream. The *Knorr* 60 silicate data when meshed with the 2nd array setting mean currents show the lowest silicate water moving primarily west, although there may be a small amount flowing east, perhaps recirculating, at 4000 m north of

(a)

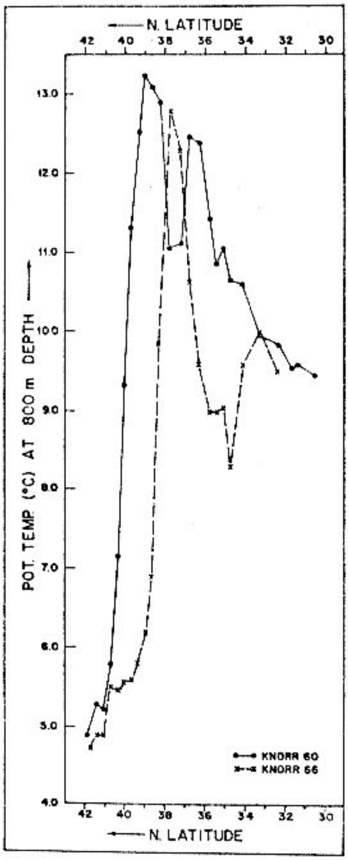


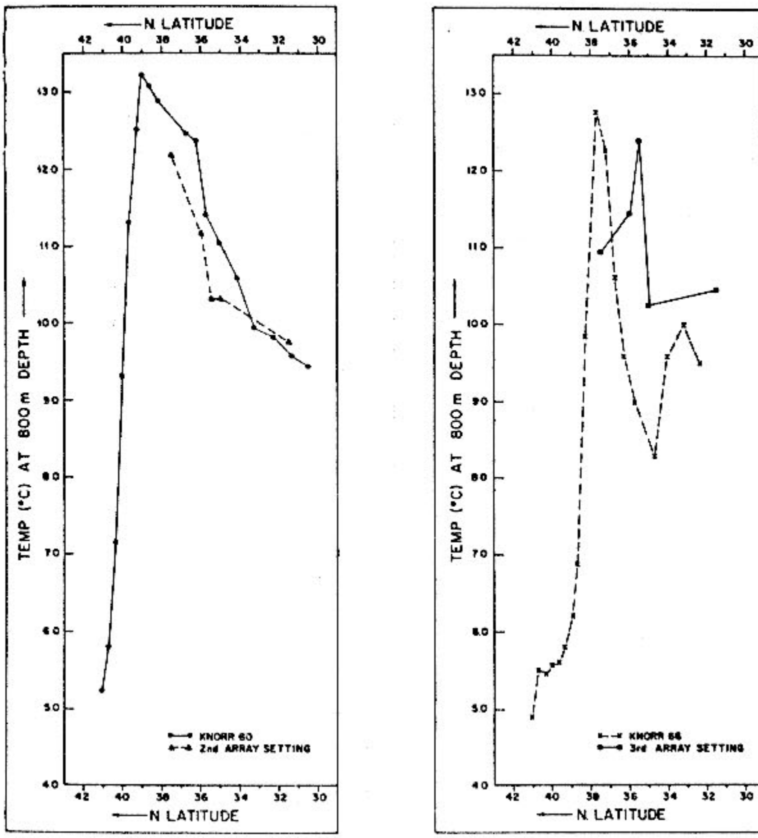
Figure 4. (a) Potential temperatures at 800 m depth from *Knorr* 60 and *Knorr* 66, using hydrographic station data only for simplicity and consistency. (b) Temperature observations from *Knorr* 60 and 66 and for the second and third array settings.

36N. For *Knorr* 66, the lowest silicates are moving pretty much west only, if merged with the 3rd array setting mean currents.

3. Summary and conclusions

An example of long-term variability has been identified in the North Atlantic along 55W, consistently depicted by both hydrographic and moored instrument data to the extent comparable. Results are based on two-year duration (nominal) moored current and temperature observations encompassing three array deployments, along with two hydrographic sections made on the setting and retrieval cruises (about nine months apart) for the third array cycle. Each data set spans both the Gulf Stream and its recirculation, the latter mean flow regime being defined here as that immediately adjacent to (offshore), and of opposite zonal flow

(b)



direction to the former. We also partially sampled the return flow, defined to be the regime offshore of the recirculation, generally weaker in mean and fluctuating current amplitude. The moored instrument observations sample the immediate proximity of the Gulf Stream at 4000 m depth only, so the hydrographic sections provide the sole information on variations in the upper level Stream as well as in water mass properties.

Intermediate-term average (to suppress mesoscale eddies) current and temperature patterns along 55W were observed to shift south by about 1.5 to 2° of latitude over approximately an 18-month period. The changes were temporally inhomogeneous. During an initial nine month (nominal) period, there was a southward shift of about 1° of latitude for one segment of the abyssal flow, along with weakening of a westward counterflow near positions of the climatological axis of the Gulf Stream. The location and structure of the recirculation did not vary essentially except in the vertical shear of zonal currents in the thermocline at the

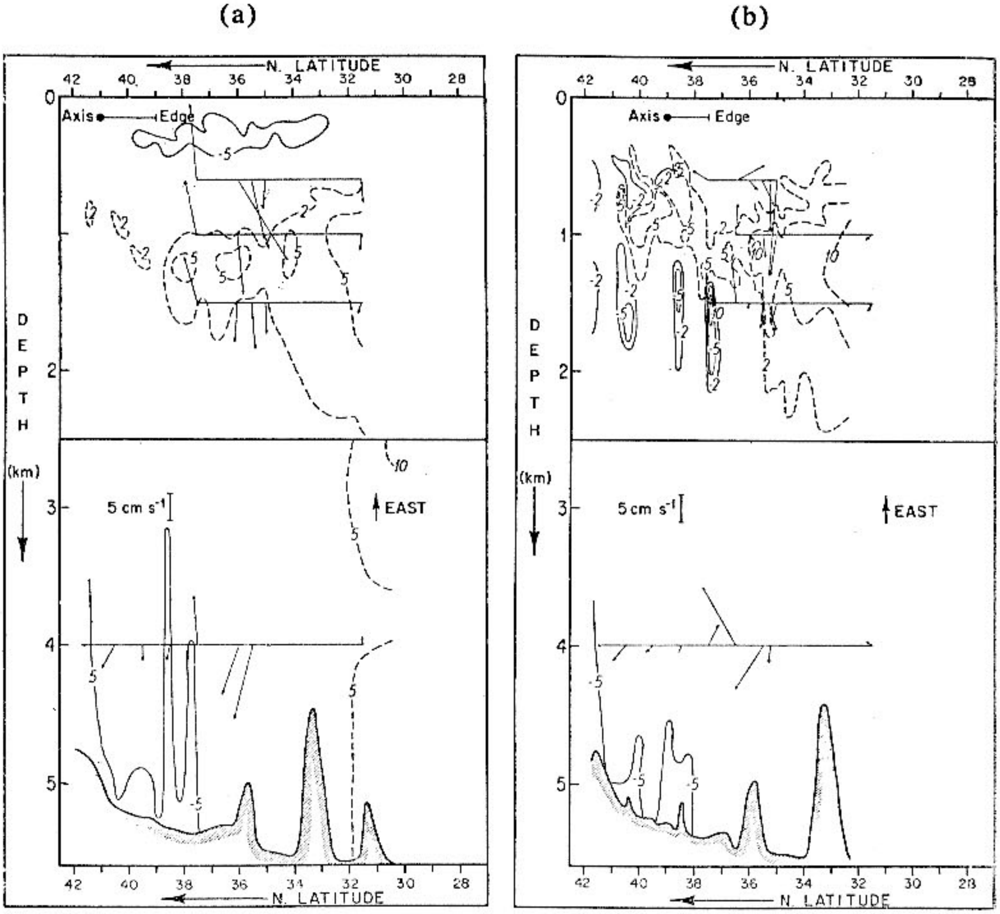


Figure 5. Mean horizontal current vectors along 55W, with selected salinity anomaly contours superimposed: (a) Second array setting and *Knorr* 60. The dot labeled axis is the location of the 15° isotherm at 200 m for *Knorr* 60. (b) Third array setting and *Knorr* 66. The dot labeled axis is the location of the 15° isotherm at 200 m for *Knorr* 66.

boundary of the recirculation and return flow. There was a change in sign of both zonal currents and their vertical shear in the return flow regime. During a second nine-month (nominal) period of observation, the flow pattern offshore of the Gulf Stream shifted to the south at all depths and the vertical shear of the recirculation increased sharply in the thermocline, with abyssal recirculation becoming weaker as well. The distinction between the recirculation and the return flow became somewhat blurred at thermocline depths.

The two hydrographic sections bracketed an interval when the mean zonal currents based on moored instrument data shifted south and increased in vertical shear in the recirculation thermocline. Similar variations occurred between the two hydrographic sections, with the added information that a southward shift also occurred in the upper level Gulf Stream, along with substantial changes in water mass properties. There was an increase in local horizontal temperature gradient in the recirculation regime between the two hydrographic sections, but no noticeable difference in total baroclinic transport (or regional temperature gradient). There was an increase in volume of the Eighteen Degree Water thermostad between the cruises, which spanned the severe winter of 1976-1977 over the North American continent. There was also a significant change in the distribution of salinity anomaly at depths above 2000 m, in contrast with a small latitudinal shift in silicate anomaly pattern below this depth. Whereas the current field shifted south, comparatively intense positive salinity anomalies in the thermocline penetrated quite far north into the Gulf Stream, while relatively strong, negative salinity anomalies in the upper deep water penetrated quite far south, across the Gulf Stream.

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REFERENCES

Armi, L. and N. A. Bray. 1982. A standard analytic curve of potential temperature vs. salinity for the western North Atlantic. J. Phys. Oceanogr., *12,* 384–387.

Bradley, K. F. 1981. A summary of Woods Hole Buoy Group moored stations for the POLYMODE Program. Woods Hole Oceanogr. Inst. Tech. Rept., W.H.O.I. Ref. 81-15.

Fisher, A. F., Jr. 1977. Historical limits of the northern edge of the Gulf Stream, *in* Gulf Stream, III(7). Monthly summary for July, 1977, published by the U.S. Dept. of Commerce.

Halliwell, G. R., Jr. and C. N. K. Mooers. 1979. The space-time structure and variability of the Shelf Water - Slope Water and Gulf Stream surface temperature fronts and associated warm-core eddies. J. Geophys. Res., *84,* 7707–7725.

Hendry, R. 1982. On the structure of the deep Gulf Stream. J. Mar. Res., *40,* 119–142.

Jenkins, W. J. 1982. On the climate of a subtropical ocean gyre: Decade timescale variations in water mass renewal in the Sargasso Sea. J. Mar. Res., *40* (Supp.), 265–290.

Leetmaa, A. 1977. Effects of the winter of 1976-1977 on the northwestern Sargasso Sea. Science, *148,* 188–189.

McCartney, M. S. 1980. Thin water mass structure in the Sargasso Sea, *in* Gulf Stream, VI(6), 3-6. Monthly summary for June, 1980, published by the U.S. Dept. of Commerce.

McCartney, M. S., L. V. Worthington and M. E. Raymer. 1980. Anomalous water mass distributions at 55W in the North Atlantic in 1977. J. Mar. Res., *38,* 147–172.

McCartney, M. S., L. V. Worthington and W. J. Schmitz, Jr. 1978. Large cyclonic rings from the Northeast Sargasso Sea. J. Geophys. Res., *83,* 901–914.

Owens, W. B. and N. G. Hogg. 1980. Oceanic observations of stratified Taylor columns near a bump. Deep-Sea Res., *27,* 1029–1045.

Richardson, P. L. 1980. Gulf Stream System: the average temperature field at a depth of 450 m.

International Council for the Exploration of the Sea (ICES) Document, C. M. 1980, Hydrography Committee C:31.
Schmitz, W. J., Jr. 1977. On the deep general circulation in the western North Atlantic. J. Mar. Res., *35*, 21–28.
—— 1978. Observations of the vertical distribution of low frequency kinetic energy in the western North Atlantic. J. Mar. Res., *36*, 295–310.
—— 1980. Weakly depth dependent segments of the North Atlantic circulation. J. Mar. Res., *38*, 111–133.
Schmitz, W. J., Jr. and W. R. Holland. 1982. A preliminary comparison of selected numerical eddy-resolving general circulation experiments with observations. J. Mar. Res., *40*, 75–117.
Schroeder, E. H. 1963. North Atlantic temperatures at a depth of 200 meters. Serial Atlas of the Marine Environment. Folio 2, American Geographical Society.
Spencer, A., C. Mills and R. E. Payne. 1979. A compilation of moored current meter data and associated oceanographic observations, Volume XIX (POLYMODE Array 1 data). Woods Hole Oceanogr. Inst. Tech. Rept., W.H.O.I. Ref. 79-34.
Talley, L. D. and M. E. Raymer. 1982. Eighteen Degree Water variability. J. Mar. Res., *40* (Supp.), 757–775.
Tarbell, S., A. Spencer and R. E. Payne. 1978. A compilation of moored current meter data and associated oceanographic observations, Volume XVII (POLYMODE Array 2 data). Woods Hole Oceanogr. Inst. Tech. Rept., W.H.O.I. Ref. 78-49.
Worthington, L. V. 1976. On the North Atlantic Circulation. The Johns Hopkins Oceanographic Studies, VI, 110 pp.

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