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On the structure of the deep Gulf Stream

by R. M. Hendry[1]

ABSTRACT

The zonal and temporal structure of the mean and low-frequency flow beneath the Gulf Stream at 55W is explored in an analysis of 17 months of current and temperature measurements at 4000 m depth. The data were obtained from a zonal array of four moorings along 40°30′N with a maximum separation of 90 km. Current speeds of up to 0.5 ms⁻¹ are observed, with r.m.s. speeds of 0.17 ms⁻¹ and a mean flow of about 0.05 ms⁻¹ toward the northwest. The temperature variability is skewed toward warm events, suggesting that the array is located near the edge of a deep zonal temperature front. Current and temperature events show a dominantly westward propagation tendency, with meridional velocity components and temperature exhibiting propagation speeds of about 15 km day⁻¹ but zonal current fluctuations propagating more than twice as fast. This suggests that there are several organized modes of variability present in the deep water. There is a statistically significant deep eddy heat flux, of uncertain origin, which is directed toward the southeast.

1. The Gulf Stream array

Ocean eddies may play an important role in the dynamics of the general circulation and the mixing of properties. The present report discusses the energetics and local zonal structure of low-frequency eddies in the deep Gulf Stream on the basis of measurements from an exploratory current meter array near 55W.

The Gulf Stream Array shown in Figure 1a was a composite of three moorings maintained by the Bedford Institute of Oceanography from December 1975, to May 1977, and a fourth mooring which was part of POLYMODE Array 2. This was a project of the Woods Hole Oceanographic Institution (W.H.O.I.) which enveloped the Bedford Institute effort in time, designed to explore the large-scale meridional structure of mean and eddy currents along 55W (Schmitz, 1977, 1978, 1980). The aim of the Gulf Stream Array was to complement this effort with a more localized, zonally-oriented exploration of the circulation along 40°30′N, near the mean latitude of the Gulf Stream as marked by the position of the 15°C isotherm at 200 m depth (Schroeder, 1963). A statistical summary of the variations of position of the surface Gulf Stream according to Fisher (1977) is reproduced as Figure 1b. The
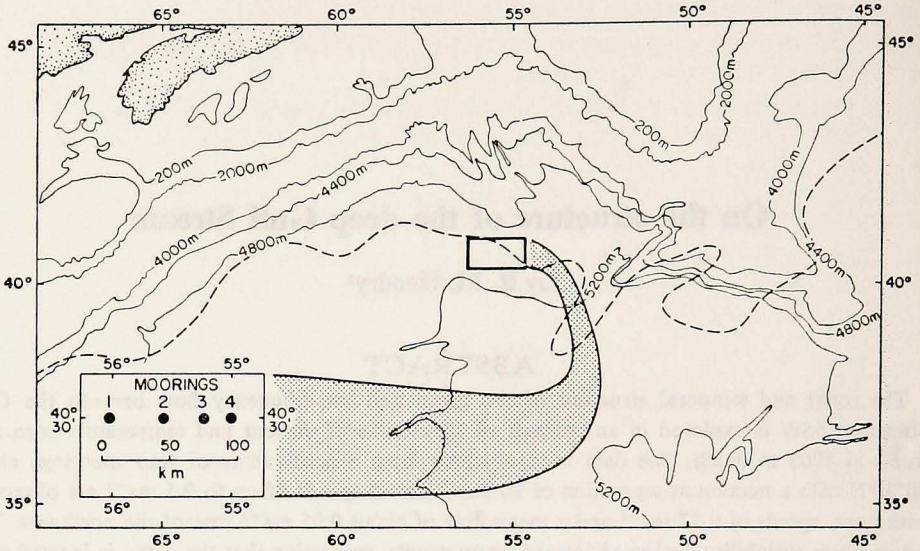
Figure 1a. Chart showing the location of the Gulf Stream Array moorings and the general bathymetry in the area. The dashed line is the mean position of the 15°C isotherm at 200 m from Schroeder (1963).
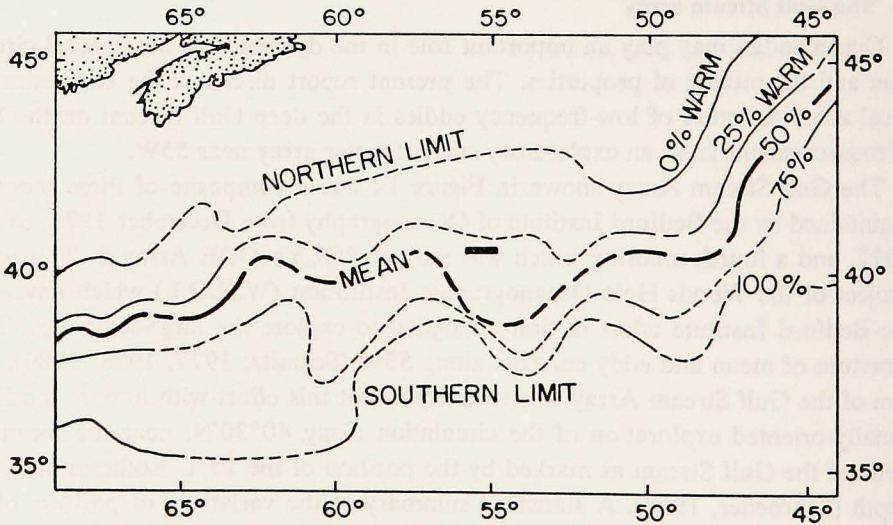

Figure 1b. Historical summary of the variations of position of the northern edge of the Gulf Stream as represented by the 15°C isotherm at 200 m according to Fisher (1977). The location of the Gulf Stream Array is shown by the solid bar near 55W.

specific goal was to obtain statistically meaningful estimates of the mean currents and the energy levels, time scales, zonal-spatial scales and propagation characteristics of eddies in the deep water beneath the Gulf Stream at 55W. This would contribute to the statistical-geographical exploration of variability in the North Atlantic which was one of the overall goals of POLYMODE.

The ocean is about 5170 m deep at the site of the Gulf Stream Array, and the 4000 m level was instrumented at all four moorings for horizontal current speed, direction and temperature measurements. On the three Bedford Institute moorings the 4800 m level was also occupied. The reason for restricting the study to these deep levels was that at present, mooring technology cannot provide measurement platforms in the stronger currents of the surface Gulf Stream.

With a limited number of moorings, it was decided to restrict the array to a linear and zonally-oriented design, and no information was obtained on the local meridional structure. The Gulf Stream is a nearly zonal jet, and from numerical simulations of time-varying ocean circulation (Holland and Lin, 1975) or by analogy with atmospheric observations it might be expected that the eddies would propagate zonally, so a zonal-wavenumber description of the deep eddies is of particular interest. POLYMODE Array 2 provides a global overview of the meridional variation of eddy energy levels and time scales along 55W (Schmitz, 1977, 1978, 1980), but it is recognized that the lack of north-south coverage on smaller scales prevents a complete description of the horizontal structure of the deep eddies in the present study.

The composite Gulf Stream Array spans a total of 90 km, with neighboring moorings at separations of about 20, 30 and 40 km. The design goal was for a spatially coherent array and the scales were suggested by earlier studies. Clarke (1976) found that deep currents at 50W in the vicinity of the Gulf Stream were coherent over 25 km horizontal separations, while Luyten (1977) observed that both mean and fluctuating currents showed little coherence at a zonal separation of 50 km beneath and to the south of the Gulf Stream at 70W. As it appears below, the array design was over-conservative for the dominant scales at 55W. The zonal scales at 70W may be influenced by the curvature of the topography associated with the continental rise there, while the topography beneath the Gulf Stream is much flatter at 55W.

2. Data sources

The three Bedford Institute moorings were equipped with Aanderaa RCM5 current meters and the moorings were supported with buoyancy located just above the 4000 m instruments. The data were obtained in three separate deployments, each of about six-months duration. At the 4000 m level complete temperature records were obtained at all sites, but the currents from the final deployment of

westernmost Mooring 1 (see Fig. 1a) were not usable. At 4800 m two of the six-month records were lost by early battery failure, including a potential backup at Mooring 1. Problems with the direction readings due to magnetization of the current meter pressure cases (Hendry and Hartling, 1979) vitiated the deeper measurements and may have contaminated the 4000 m results as well, with systematic errors of tens of degrees possibly present at some orientations. The shallower records were analyzed with nominal direction calibrations and any detailed results depend on internal consistency and intercomparison with the POLYMODE Array 2 mooring for full justification.

The original current meter records from 40°30'N, 55W at 4000 m in POLY-MODE Array 2 were obtained from Dr. W. J. Schmitz, Jr. at W.H.O.I. and incorporated in the present analysis. Instrumentation and mooring construction of Array 2 moorings were different from the three Bedford Institute moorings, and the data from the POLYMODE mooring provide independent results as far as any measurement errors are concerned.

The absolute calibration of temperature needs some comment. At 4000 m the total variation in temperature was about 0.3°C. The temperature calibration of the Aanderaa instruments was available only to 0.1°C and a further correction was necessary to combine records from different instruments at the same site in a continuous series. There was typically a gap of one or two days between the end of one record and the start of its replacement, and temperature variations in the interim prevented a straightforward correction to a common datum. The POLYMODE mooring incorporated in the Gulf Stream Array provided a continuous record with temperature calibration good to 0.01°C (Payne *et al.*, 1976), and the temperature from each individual 4000 m RCM was offset to make the mean temperature over the record equal to the mean measured over the corresponding period at the Array 2 mooring. In cases when the gap between settings was as little as 20 hours and the temperature variability was small, the resulting temperature series were continuous across the gap to within the instrumental least count of about 0.02°C.

All time series were smoothed with a truncated Gaussian filter with halfwidth 24 hours to remove the relatively weak tidal and internal wave variability at shorter periods and the resulting smoothed series were subsampled at 12-hour intervals.

3. Observational results

As an overview, time series of velocity at the four sites are presented in stick diagram form as Figure 2 and corresponding temperature plots are given in Figure 3. The velocity plots give the impression of a flow field dominated by time-dependent features, with bursts of current of up to two-months duration and typical amplitudes of 0.3 ms^{-1}. The visual similarity between moorings shows that the scales of the array were appropriate to a coherent local experiment. One particularly
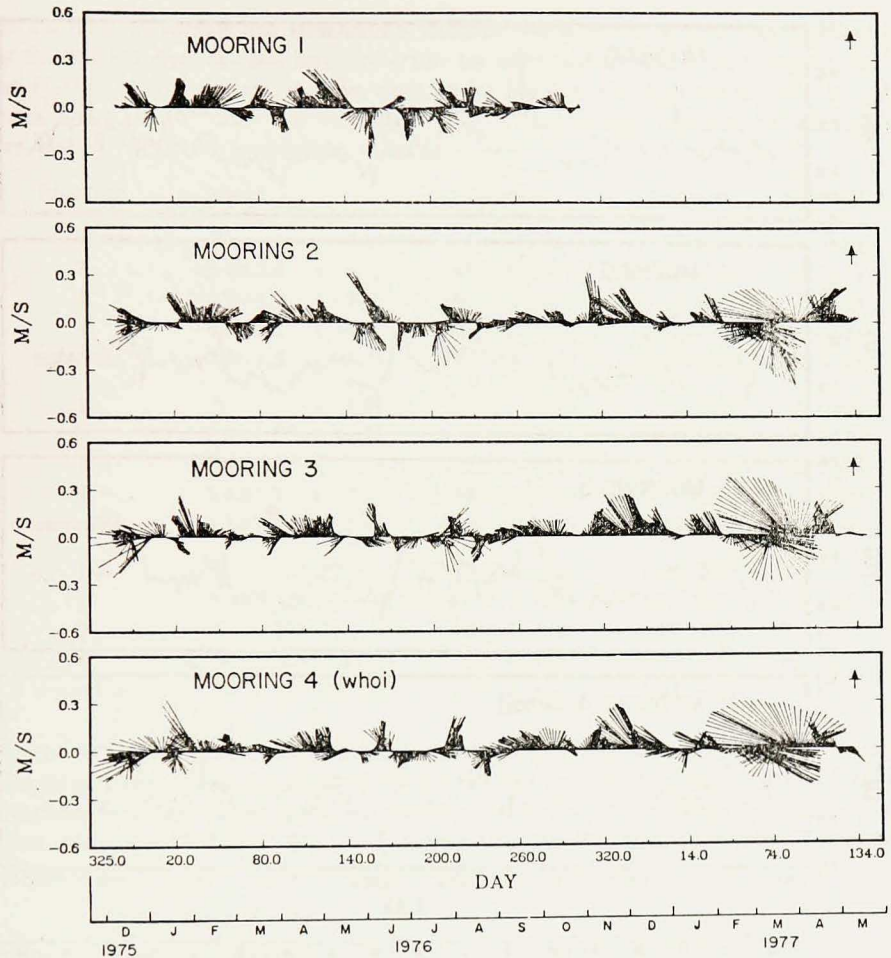
Figure 2. Stick diagram time series of low-pass filtered horizontal currents at 4000 m. North is up in the figures, as indicated by the small arrows.

noticeable current event toward the end of the measurement period produced speeds of over 0.5 ms^{-1}; as will be seen, this one event has an influential effect on the overall velocity statistics. The temperature records show intermittent warm events, accompanied by variability on about the same time scales as the current bursts and by trends of many months duration. The aim of this section is to quantify these impressions and examine more closely the spatial and temporal structure of the measured fields.

a. Overall statistics. Table 1 presents an overall summary of statistics for both the full measurement period and for the first 11 months when velocities were obtained
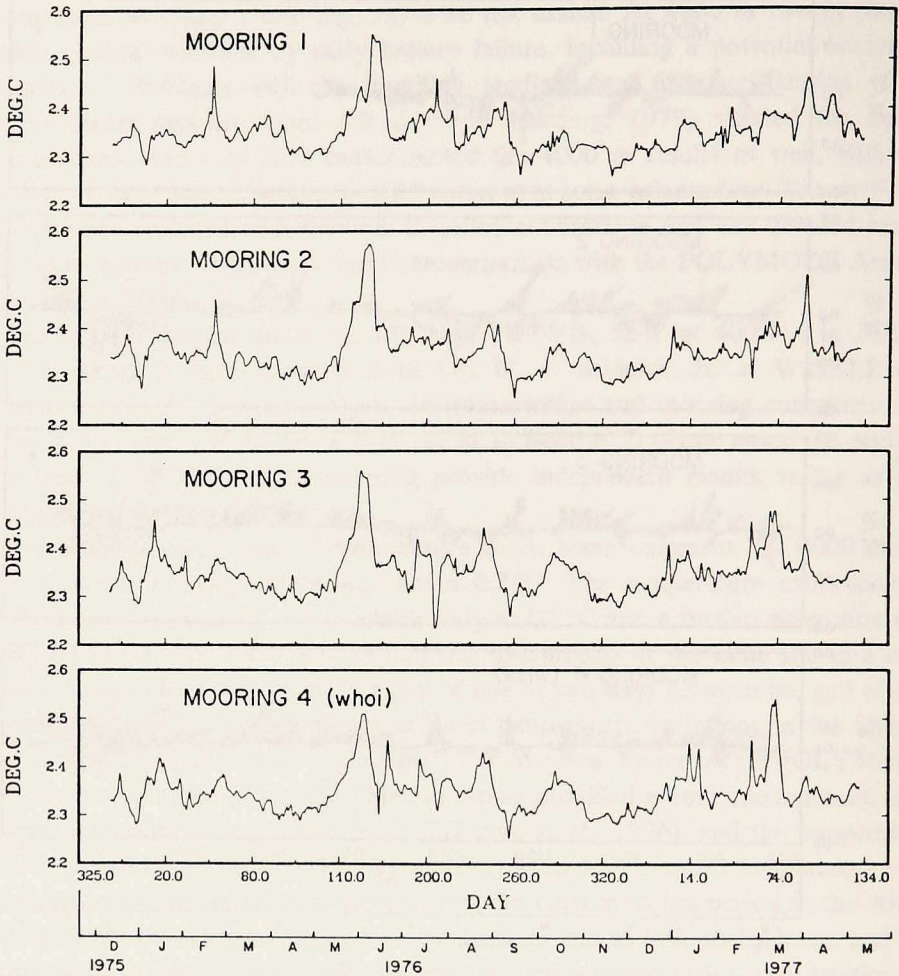
Figure 3. Time series of low-pass filtered temperature at 4000 m.

at all four sites. Included in the table are standard errors for means, variances and covariances estimated from the covariability of the data (Bendat and Piersol, 1966). Ensemble means are obtained by averaging the results from different moorings. The standard errors for the ensemble averages are the r.m.s. standard error for individual estimates, which is a conservative estimate since the variability at spatially separated points is not perfectly correlated.

A mean flow of about 0.05 ms^{-1} directed to the northwest was found at each of the three moorings where currents were available for a common period of 513 days, or just over 17 months. Estimates of the means over the first 11 months alone were changed by no more than 0.01 ms^{-1} in speed or 30° in direction by the additional

Table 1a. 4000 m current and temperature statistics (mean, variance, skewness and kurtosis) for the full 513 days of data. Standard errors for estimates of means and variances (Bendat and Piersol, 1966) are given, and the statistics for the first 325 days are included in parentheses. Units are 10^{-2} ms^{-1} for velocity, 10^{-4} m^{2}s^{-2} for velocity variance, °C for temperature, and 10^{-4} (°C)^2 for temperature variance.

	Mooring	Mean		Variance		Skewness	Kurtosis
U	1	*	(−2.8)	*	(94)	* (0.2)	* (2.6)
	2	−3.9±1.8	(−4.7)	143±28	(77)	0.3 (0.1)	4.5 (2.5)
	3	−2.7±1.7	(−3.4)	160±32	(82)	0.7 (−0.1)	5.7 (3.0)
	4	−4.0±1.8	(−4.0)	196±39	(100)	0.4 (−0.2)	4.9 (2.7)
	ensemble	−3.5±1.8	(−3.7)	166±33	(88)	0.5 (−0.0)	5.0 (2.7)
V	1	*	(1.8)	*	(93)	* (−0.4)	* (3.0)
	2	2.5±1.5	(1.6)	121±23	(83)	−0.5 (0.1)	4.1 (3.5)
	3	4.0±1.6	(1.7)	112±21	(71)	0.1 (−0.1)	3.6 (2.9)
	4	3.4±1.3	(2.5)	98±19	(75)	−0.1 (0.1)	3.0 (2.7)
	ensemble	3.3±1.5	(1.9)	110±21	(81)	−0.2 (−0.1)	3.6 (3.0)
T	1	* ±0.009 (*)		18± 4	(20)	1.5 (1.9)	7.3 (8.2)
	2	* ±0.009 (*)		20± 4	(24)	1.8 (2.0)	9.3 (9.2)
	3	* ±0.008 (*)		20± 4	(23)	1.4 (1.5)	7.1 (7.6)
	4	2.350±0.007 (2.352)		18± 4	(16)	1.4 (1.1)	6.3 (5.2)
	ensemble	* (*)		19± 4	(21)	1.5 (1.6)	7.5 (7.6)

Table 1b. 4000 m current and temperature statistics (speed and direction of mean flow and velocity and temperature covariances) for the full 513 days of data. Standard errors for the covariance estimates are given and the statistics for the first 325 days are included in parentheses. Units are 10^{-2} ms^{-1} for speed, degress true for direction, 10^{-4} m^{2}s^{-2} for velocity covariance and 10^{-2} ms^{-1} °C for velocity-temperature covariance.

	Mean				
Mooring	Speed	Direction	$\overline{u'v'}$	$\overline{u'T'}$	$\overline{v'T'}$
1	* (3.3)	* (304)	* (−13)	* (0.12)	* (−0.14)
2	4.6 (5.0)	302 (288)	−39±18 (−23)	0.14±0.08 (0.14)	−0.10±0.07 (−0.08)
3	4.8 (3.8)	326 (297)	−44±18 (− 9)	0.18±0.08 (0.15)	−0.13±0.07 (−0.03)
4	5.2 (4.7)	310 (302)	−42±19 (− 1)	0.23±0.08 (0.20)	−0.14±0.06 (−0.06)
ensemble	4.8 (4.2)	313 (297)	−42±18 (−12)	0.18±0.08 (0.15)	−0.12±0.07 (−0.08)

6 months of data. In general the estimates of the components of mean flow are about two standard errors different from zero. From the error statistics of the 513-day records, it can be estimated that about 18 years of data would be needed to measure the mean u (east) component to within a standard error of 0.005 ms^{-1}, and about 12 years for a similar estimate of the mean v (north) component since the estimated variance of the v component is less. There is no statistically-significant zonal change in the mean flow over the 90 km array, in contrast to the zonal inhomogeneity at 70W reported by Luyten (1977).

The time-varying currents are characterized by an overall r.m.s. current fluctuation of 0.17 ms^{-1} over 17 months. The standard errors of variance for both u and v components are about 20% of the overall estimates. For the first 11 months, the ensemble-averaged variance was only 60% of the estimate for the full measurement period including the high speeds during March and April 1977. The difference between the 11-month and 17-month variance statistics suggests that the strongest eddies occur infrequently on time scales of one year, but if the 17-month results are representative, it can be estimated that four times the present length of record, or about six years, is required to reduce the standard error to 10% of the actual variance. For the full 17 months there is about 50% more variance in the u component than the v component, with the difference being almost two standard errors for the u variance.

The covariance between u and v velocity component fluctuations $(\overline{u'v'})$ given in Table 1 can be combined with the individual component variances to define principal axes for the current variations. The principal axes for the 17-month records are oriented north of west, ranging in direction from 290°T to 307°T, and there is about twice as much variance in this direction as in flow at right angles to the principal axes. The 11-month statistics are similar, with a range of directions of the principal axes from 272°T to 319°T and somewhat less linear polarization in the principal direction.

The $\overline{u'v'}$ term can be interpreted as the northward eddy flux of eastward momentum per unit mass, and Schmitz (1977) has described the large-scale variation of $\overline{u'v'}$ along 55W and discussed a possible significance with respect to the deep mean flow. The 17-month results from the Gulf Stream Array average $-42 \pm 18 \times 10^{-4}$ m^{2}s^{-2} for $\overline{u'v'}$ at 40°30′N, with no significant zonal variation over 50 km. The standard error is just more than 40% of the magnitude of the estimate, and to reduce this to 10% might mean that 16 times as much data, about 25 years, would be required. The 11-month estimates of $\overline{u'v'}$ range from -1 to -23×10^{-4} m^{2}s^{-2} over a 90 km zonal span, for an ensemble estimate of about $-12 \pm 13 \times 10^{-4}$ m^{2}s^{-2}. The correlation coefficient between u and v fluctuations is more stable in time than the covariance, changing from -0.14 over 11 months to -0.30 over 17 months while the covariance increases by more than a factor of three. The confidence interval of two standard errors for the 17-month covariance estimates includes three of the four individual 11-month estimates.

Along with the tendency to linear polarization, the current fluctuations show a rotary nature with an inspection of Figure 2 suggesting a predominance of clockwise rotation of the horizontal current vector with time. This is confirmed by a rotary spectral decomposition of the time series, and for the full period of measurement there is about 1.8 times as much energy in clockwise rotating currents as in anticlockwise rotation. This kinematical feature of the variability might be related

to the propagation of eddies of a particular form through the array, as discussed in more detail below.

The temperature fluctuations over 17 months have an ensemble-average variance of $19 \pm 4 \times 10^{-4}$ °C², corresponding to 100 m r.m.s. isotherm depth fluctuations at 4000 m. The visual impression of a series of warm events is characterized by a skewness of about 1.5, compared to zero for a Gaussian process, and an estimated kurtosis of about 8 or more than double the Gaussian value of three.

Surveys of the Gulf Stream near 55W (Fuglister, 1963) find horizontal temperature gradients in the deep water associated with the strong horizontal gradients in the Gulf Stream thermocline. There is a general impression of a deep transition region beneath the Gulf Stream between the interior of the gyre and the colder Slope Water, with the 4000 m temperature changing from about 2.4°C in the interior to 2.3°C at the continental slope where the 2.4°C isotherm shallows to perhaps 3500 m. The warm events rising above a relatively cold background in Figure 3 suggest that the Gulf Stream Array is located near the northern edge of a deep transition region. The warm events at 4000 m might be either extreme northward excursions of a continuous deep front or the deep signatures of isolated warm eddies, as discussed more fully in the next section.

Table 1 also gives the covariance between velocity and temperature fluctuations. Overall averages from the three 17-month records are $\overline{u'T'} = 18 \pm 8 \times 10^{-4} \text{ms}^{-1}$ °C and $\overline{v'T'} = -12 \pm 7 \times 10^{-4} \text{ms}^{-1}$°C. Both estimates are different from zero by about two standard errors, with somewhat more relative uncertainty in the meridional component. The velocity-temperature covariance estimates do not vary significantly among individual moorings for either the first 11 months or the whole data set. Since the 17-month statistics give standard errors about 50% as large as the magnitudes of these covariances, about 25 times more data, 35 years, may be required to reduce the relative standard error to 10%. The eddy heat flux associated with the measured covariances is of order 10^4 Wm⁻² directed to the southeast. Since mooring motion can contaminate such estimates, it is noteworthy that the two different mooring designs in the array gave similar results.

b. Time scales. The error analysis above has implicitly defined an integral time scale

$$\tau_I = \int_0^\infty R_x(t)dt \tag{1}$$

for a stationary, continuous, random process $x(t)$ with autocorrelation function $R_x(t)$. The mean square departure of an average of $x(t)$ over a time interval T from the true mean is

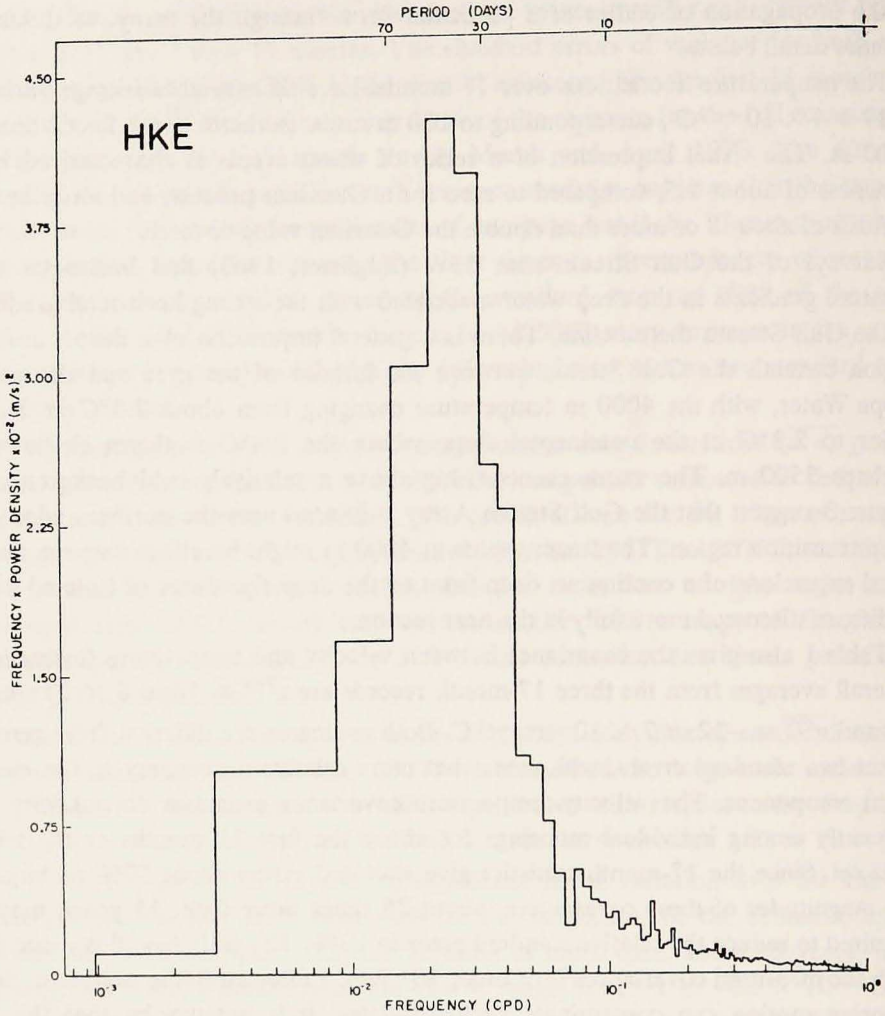$$\sigma^2(\bar{x}) = (2\sigma^2{}_x/T) \int_0^T (1 - t/T)R_x(t)dt \tag{2}$$

Figure 4. The ensemble-averaged spectrum of horizontal current variance at 4000 m depth from 17 months of record at Moorings 2, 3 and 4. The estimates were obtained by averaging over three adjacent frequency bands in the raw periodograms.

or approximately $2\sigma^2_x \tau_I / T$, where σ^2_x is the variance of $x(t)$ (Bendat and Piersol, 1966). In practice, with a finite sample of length T the autocorrelation function can be estimated only at lags less than T, and conventionally only lags up to about $T/10$ are considered for stability reasons. Thus in practice an expression analogous to the integral in (2) above must be used to estimate τ_I. For the 17-month records from the Gulf Stream Array, the integral time scale for either u or v components is estimated to be about 5 days, while for temperature the corresponding estimate is somewhat longer at about 9 days.

Spectral analysis was used to quantify the variability of velocity and temperature on different time scales, and the results for the currents are summarized in an ensemble-averaged spectrum of horizontal current variance for 17 months at Moorings 2, 3 and 4 which is shown in Figure 4. About 60% of the total variance is contained in a broad peak between 20-day and 70-day periods which can be characterized as the mesoscale eddy band. A further 30% of the variance comes from motions with periods longer than 70 days, while the remaining 10% comes from the high-frequency tail of the spectrum.

An average temperature variance spectrum for the total measurement period at all four moorings is shown in Figure 5. Over 50% of the variance arises from fluctuations with periods greater than 70 days, compared to about 30% of the current variance in the same band—the temperature spectrum is considerably "redder" than the horizontal current spectrum. There is some structure in the eddy band of the temperature spectrum, but the structure may come from the intermittency of the temperature events rather than any favored periodicities in the eddy band. In the 17-month analysis, the average spectrum had about 3% of the total power at periods longer than one year, as represented by the 513-day harmonic, and considering the uncertainties in temperature calibration, this is negligible. If there are trends with time scales longer than one year, considerably longer time series are needed to resolve them.

Spectral analysis can also be used to determine the time scales that dominate the covariance between velocity components or velocity and temperature. An ensemble-averaged cospectrum between east and north currents prepared by averaging over the results from the 17-month records is presented in Figure 6. Almost exactly half of the overall covariance of -42×10^{-4} m^{2}s^{-2} comes from each of the eddy band and longer period band as defined above, with a negligible contribution from the higher frequencies. Although the results from the three individual moorings differ in details, the partition of covariance in these broader frequency classes is similar. In the analyses of the first 11 months of data, great variability was observed among current cospectral estimates at the four moorings, consistent with the suggested low-frequency content, and the estimates of $\overline{u'v'}$ at the four sites show some scatter. There was a distortion of the u-v cospectrum at westernmost Mooring 1 which suggests that the direction problems mentioned above may have affected the structure of this particular record.

Similar average cospectra for velocity components and temperature are given in Figure 7. For the 17-month analysis about 55% of the u-T covariance and 65% of the v-T covariance arise from periods greater than 70 days, and about 40% and 30% respectively from the eddy band. The velocity-temperature cospectra are relatively more energetic at the lower frequencies than the velocity spectra, with about the same distribution at the temperature spectra. The dominance of the cospectra by a few of the longest record harmonics corresponds to the large relative errors derived for $\overline{u'T'}$ and $\overline{v'T'}$ in the time-domain error analysis.
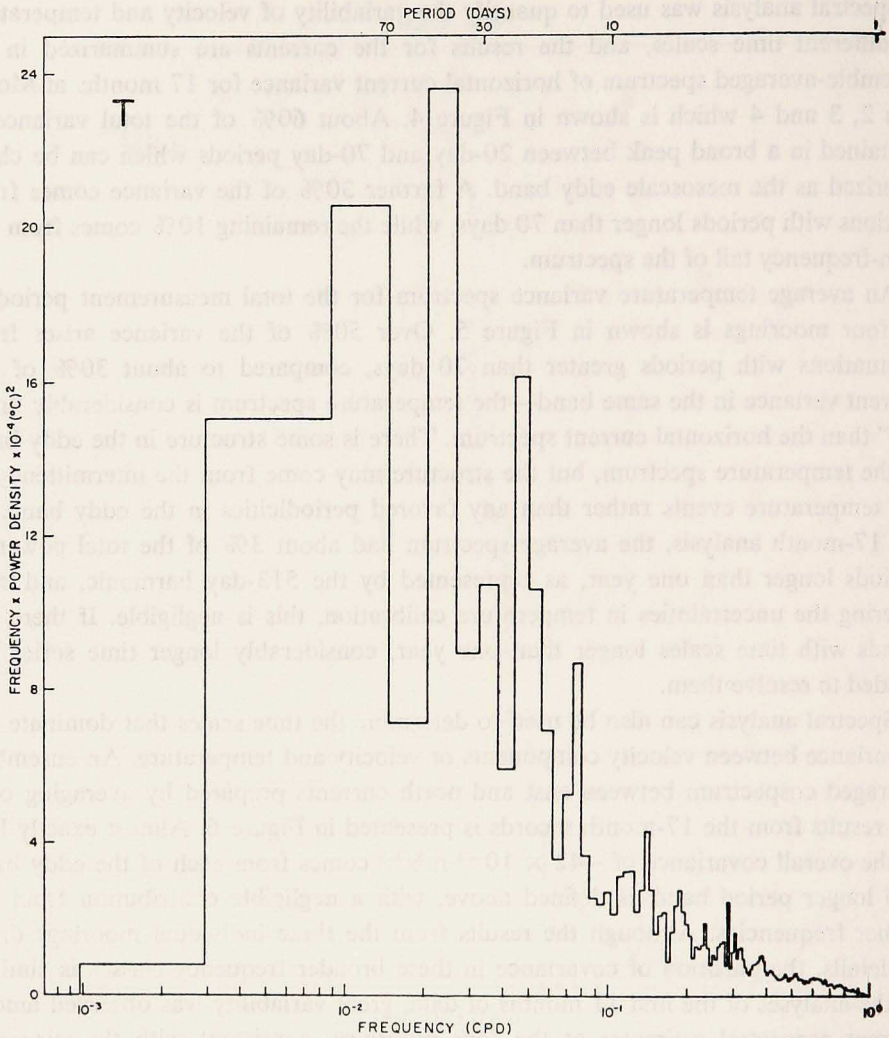
Figure 5. The ensemble-averaged spectrum of temperature variance at 4000 m from 17 months of record at all four moorings, calculated in the same way as for Figure 4.

c. Zonal scales. The overall zonal spatial scales of current and temperature fluctuations are quantified by estimates of the spatial correlation functions shown in Figure 8. The full set of zonal lags between 20 and 90 km is available for only the first 11 months for currents, and the 11-month estimates are shown separately in Figure 8. The standard error associated with each 11-month estimate is shown in the figure, and the error bars for the 17-month estimates are typically about 10 percent smaller. Both u component and temperature fluctuations are positively correlated at all the available separations, with correlation coefficients decreasing with increas-
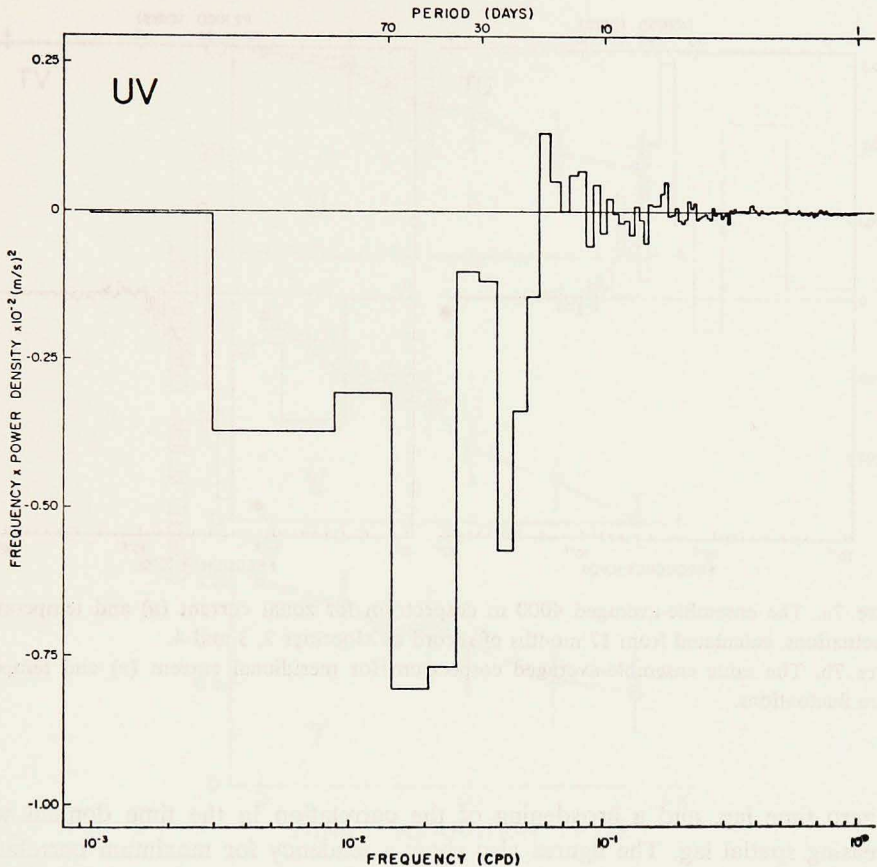
Figure 6. The ensemble-averaged 4000 m cospectrum between *u* and *v* velocity components, calculated from 17 months of record at Moorings 2, 3 and 4.

ing separation to about 0.5 at the maximum 90 km. The choice of separations in the array was overly conservative in the sense that sampling over greater distances could have provided more information. The *v* component correlation decreased more rapidly than the *u* component, just vanishing at the 90 km lag. The *v* component is transverse to the array orientation, and for a spatially homogeneous and isotropic field of two-dimensional eddies the vanishing of the transverse velocity correlation at the 90 km lag would indicate a characteristic eddy diameter of 180 km.

d. Space-time structure: zonal propagation. Figures 9a, b and c are contour maps of space-time correlations for velocity components and temperature as a function of zonal and temporal lag, with spatial lags of 20, 30 and 50 km available for *u* and *v* and lags up to 90 km for temperature from the full 17-month records. These figures show the decrease in correlation with increasing zonal separation seen in Figure 8
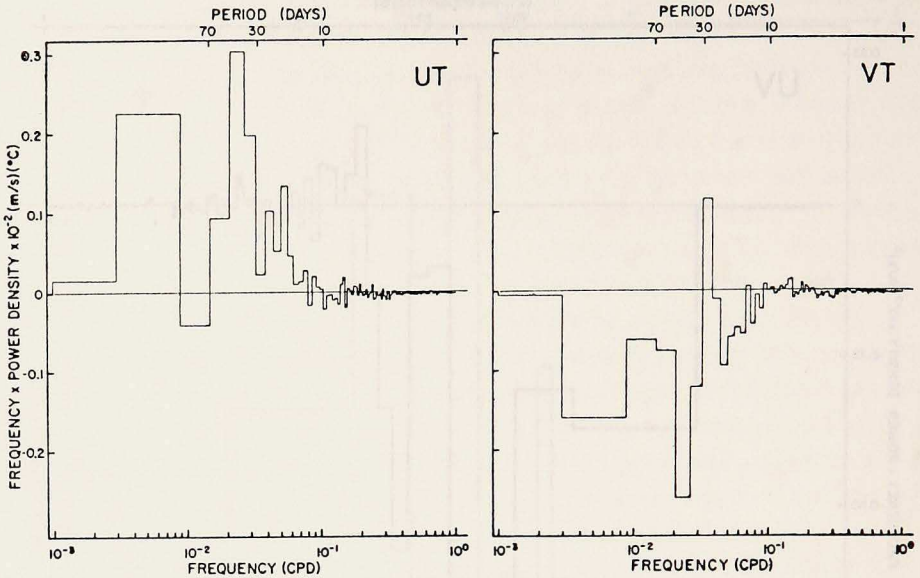
Figure 7a. The ensemble-averaged 4000 m cospectrum for zonal current (u) and temperature fluctuations, calculated from 17 months of record at Moorings 2, 3 and 4.

Figure 7b. The same ensemble-averaged cospectrum for meridional current (v) and temperature fluctuations.

for zero time lag, and a broadening of the correlation in the time domain with increasing spatial lag. The figures also show a tendency for maximum correlation at non-zero time lag for zonally separated points, in the sense that eastern moorings lead western ones and suggesting westward propagation. The standard errors for the correlation estimates vary from just less than 0.2 for maximum correlations to between 0.1 and 0.2 at the 0.4 correlation contour.

The ratio of zonal separation and the time lag at which maximum correlation is found defines a convection speed, so called because in a case where the turbulent fluctuations in a flow are much less than the mean flow, the time lags arise by the advection or convection of the turbulent eddies by the mean flow. In order to quantify the propagation tendencies and test the statistical significance of the results, linear least-squares fits of the distribution of time lag for maximum correlation versus zonal separation, constrained to pass through the origin, were made. This model of a constant convection speed gave speeds of 37 km day^{-1} for the u component, 14 km day^{-1} for the v component and 17 km day^{-1} for temperature fluctuations in the 17-month analysis. An error analysis for the slope of a constrained least-squares fit (Green and Margerison, 1978) gives $1 - \propto$ confidence limits of
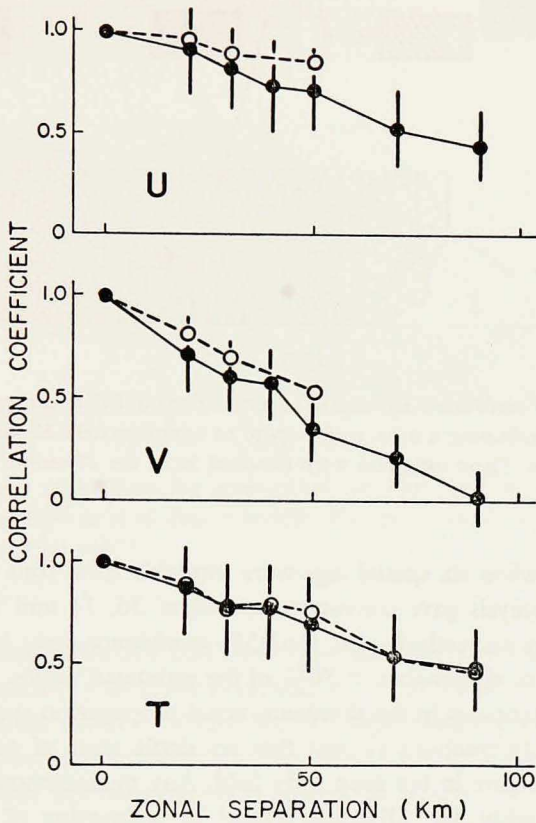
Figure 8. Zonal correlation functions for u and v components and temperature as a function of separation at 4000 m. Estimates at lags of up to 90 km for 11 months duration are shown as solid circles, and estimates for the full 17 months of measurement are shown as open circles. The error bars are the standard errors for each 11-month estimate.

$$\pm t_{n-1} (1 - \propto/2) \{\Sigma D_j^2/(n-1)\}/\{\Sigma x_j^2\}$$

where $t_{n-1} (1 - \propto/2)$ is the $1 - \propto/2$ percentage point for Student's t distribution with $n-1$ degrees of freedom, n is the number of lags, x_j, D_j is the difference between the fit and the actual time lag for maximum correlation at lag x_j, and the sums are over all n lags. The 95% error bars for the 17-month fits are about $\pm 60\%$ of the estimated slopes for u or v with three lags, and $\pm 30\%$ for temperature with six lags. The 37 km day^{-1} convection speed for u is significantly greater than the estimate of 14 km day^{-1} for v at the 95% confidence level as determined by a similar t-test for the difference of two slopes. The estimate of 17 km day^{-1} for temperature fluctuations is intermediate to the results for u and v, but not distinguishable from the v component estimate at 95% confidence. For the
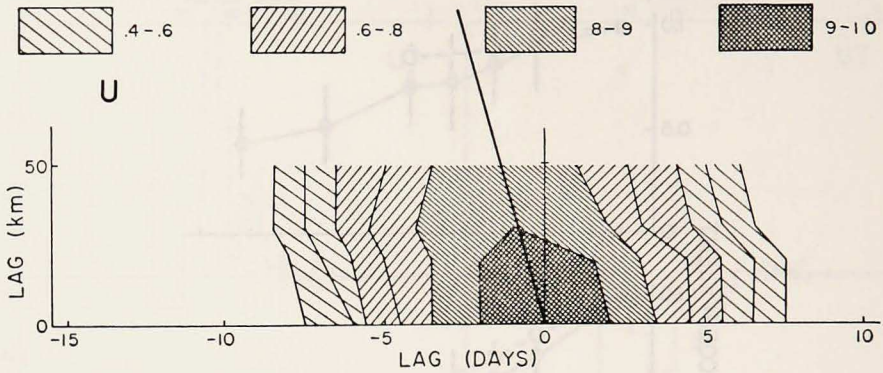
Figure 9a. Space-time correlation estimates for zonally separated u components (longitudinal correlation). A ray indicating a propagation speed of approximately 37 km day^{-1} to the west is given in the figure. These estimates were obtained from the 17-month 4000 m records at Moorings 2, 3 and 4.

11-month records, when six spatial lags were available from four moorings, a similar least-squares analysis gave convection speeds of 36, 11 and 17 km day^{-1} for u, v and temperature respectively, and the 95% confidence error bars on the slopes of the fitted lines were all less than $\pm$ 30% of the estimated slopes.

The apparent differences in the dominant zonal propagation speeds of zonal and meridional velocity fluctuations suggest that no single class of eddies can explain the propagation structure in the deep eddy field. Any monochromatic wave, or any single propagating eddy, has all fields related by a function of the form $f(x-ct)$ where the spatial coordinate x and the temporal coordinate t are related by a phase speed or convection speed c. Since there is an estimated linear correlation of 0.3 between u and v fluctuations, about 30% of the variance in u and v is predictable
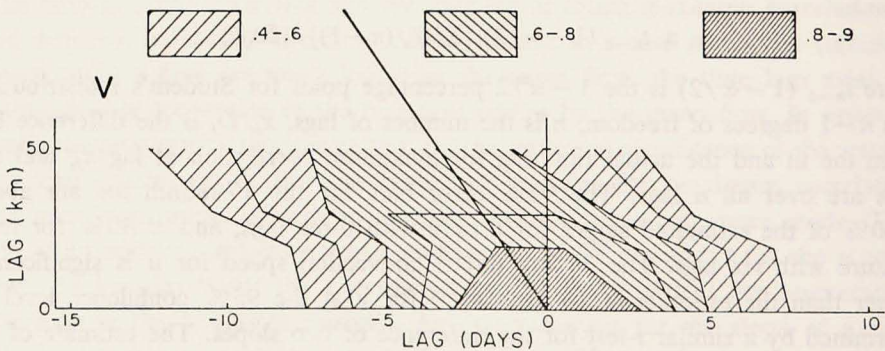

Figure 9b. Space-time correlations for zonally separated v components (transverse correlations) as in Figure 9a. The trend line shows westward propagation at approximately 14 km day^{-1}.
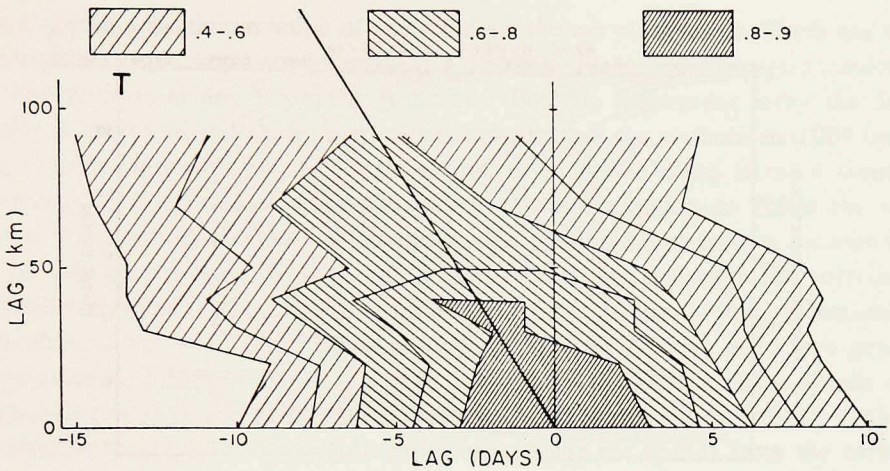
Figure 9c. Space-time correlations for temperature for zonal lags of up to 90 km from 17 months of data at 4000 m at all four moorings. The trend line shows westward propagation at approximately 17 km day⁻¹.

from a simple linear projection that would give identical propagation characteristics. Because of this tendency to linear polarization, a correlation analysis was done for velocity components resolved along 300°T, approximately the principal axis of variance, and the orthogonal direction. The zonal convection speeds for components resolved in this way fell between the estimates for u and v in the unrotated frame of reference. As another approach, the vector velocity time series were decomposed into two circularly-polarized time series and the correlations done for the clockwise and anticlockwise rotating parts separately. The result was a convection speed to the west of 22 km day⁻¹ for the more energetic clockwise polarization over the full 17 months, and a nearly identical 23 km day⁻¹ for the anticlockwise currents. Over the first 11 months, somewhat different results were obtained with convection speeds of 22 km day⁻¹ for clockwise polarization but only 15 km day⁻¹ for anti-clockwise currents. In all cases the results fell between the estimates for u and v components, suggesting that the most extreme differences in propagation tendency are associated with linearly-polarized zonal and meridional current components. The presence of two distinct rates of propagation suggests that at least two struc-tured modes of variability are present in the field of motion beneath the Gulf Stream.

Conventional frequency-zonal wavenumber power spectra for u, v and tempera-ture fluctuations were computed from the 17-month records and the results are shown in Figure 10. The tendency for westward propagation in all three variables is clearly shown in these figures by the predominance of power at positive zonal wavenumbers. The spectra are normalized by the total power in a given frequency
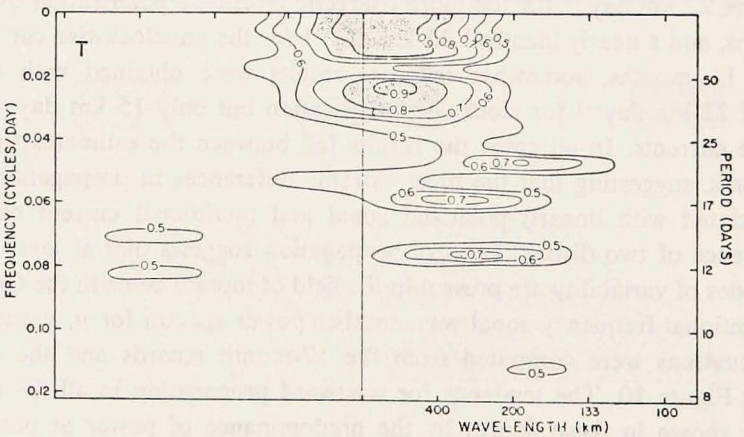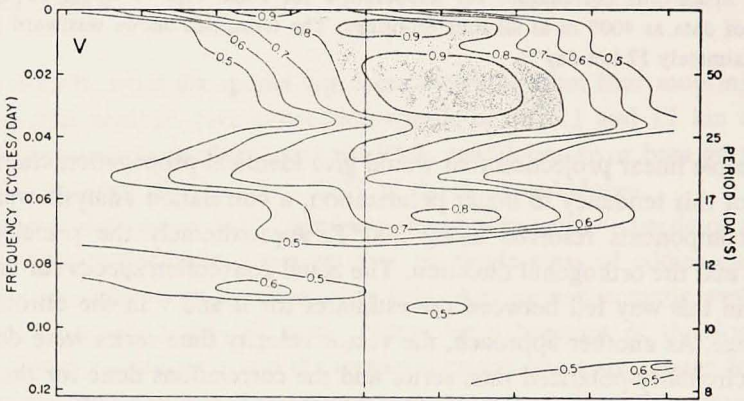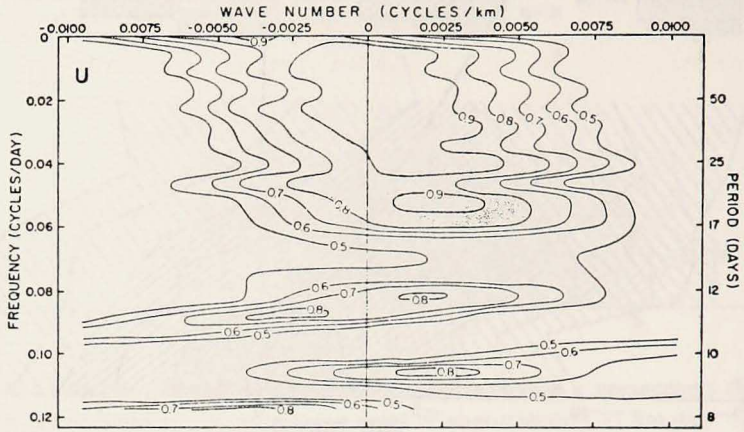
band, giving a maximum value of unity for a noiseless plane wave. There are only three points in the zonal array for u and v, and four for temperature, and resolution in wavenumber at any frequency is limited. For the three-point array the 50% power points of the main lobe in the array beampattern are at about ± 0.004 cycles km^{-1} from the maximum and the distribution of power along lines of constant frequency in Figure 10 is essentially given by this beampattern. Since the total power in current fluctuations and especially temperature fluctuations is concentrated at periods greater than 30 days, the longer time scales dominate the correlation estimates discussed above. However the less energetic, higher frequency fluctuations also show a westward propagation tendency in Figure 10 and there is a general impression of a concentration of energy along rays of constant phase speeds corresponding more or less to the convection speeds derived in the correlation analysis. A constant phase speed dispersion relationship using the speeds from the correlation analysis gives zonal wavelengths of between 1000 and 4000 km for u component variability with periods between 30 and 120 days, and shorter scales between 400 and 2000 km for v components or temperature fluctuations with the same periods.

It was noted earlier that there was a dominant tendency for clockwise rotation of the horizontal currents with time. The westward propagation of meanders of a zonal current that are convex northward will give rise to predominantly clockwise rotating currents as a fixed point. Such a pattern of meanders or isolated current rings is generally consistent with the suggested location of the Gulf Stream Array near the northward boundary of a deep transition region.

The one-dimensional nature of the data set makes it impossible to comprehensively explore the structure in the horizontal velocity field. More detailed analysis of the data is possible, such as decomposing the current variability into empirical orthogonal modes, but this will not be pursued in the present paper.

4. Discussion

The preceding section has given a kinematical and statistical description of the data from the Gulf Stream Array, showing a flow with mean value of about 0.05 ms^{-1} to the northwest and an energetic, structured variability. Although the array is located beneath the Gulf Stream, there is a fundamental question as to whether or not the mean Gulf Stream extends vertically into the deepest levels as a coherent

Figure 10a. Conventional zonal wavenumber-frequency spectrum for u components at 4000 m from 17 months of data at Moorings 2, 3 and 4. A noiseless plane wave would give unit power. The averaging in the frequency domain is the same as for the spectrum in Figure 4, and the poor resolution in wavenumber due to the limited number of points in the zonal array is evident. Westward phase propagation gives power at positive zonal wavenumber. b. Similar to a. for v components. c. Conventional zonal wavenumber-frequency spectrum for temperature fluctuations at 4000 m from 17 months of record at all four moorings.

current. The mean flow at 55W in the deep water has a westward component which is reversed compared to the surface Gulf Stream. At 70W, Luyten (1977) also described a westward, along-isobath mean flow north of the 4000 m depth contour beneath and to the north of the mean Gulf Stream. Schmitz (1980) has discussed the meridional variation of mean flows along 55W, finding a westward mean flow at 4000 m at 39°30′N as well as at the 40°30′N POLYMODE Array 2 site discussed in this paper. Numerical models that resolve mesoscale eddies have produced mean flows beneath a model Gulf Stream as a consequence of the stresses produced by eddies in the upper layer (Holland, 1978). If this mechanism is important in the real ocean, the deep mean flow may be only indirectly related to the mean surface Gulf Stream. Some authors have associated the deep westward mean flow with a Western Boundary Undercurrent carrying remnants of Denmark Strait overflow water along the continental slope as far as Cape Hatteras, on the basis of the distribution of dissolved silicate (McCartney et al., 1980). More information is needed on both the vertical and zonal extent of this deep mean flow regime.

There is also a question as to the vertical structure of the time-dependent fluctuations. Richardson et al. (1979) discussed several vertical profiles of horizontal velocity in a detached, cold core Gulf Stream ring a few months after its formation. They showed currents with strong mean shears between the surface and 1000 m and more gradual shear extending possibly to the bottom, but the cyclonic circulation associated with the ring was unambiguously present only between the surface and 2000 m. The cold core of the eddy appeared to extend all the way to the bottom at 5000 m. McCartney et al. (1978) reported on the vertical structure of a large, cyclonic cold eddy in the eastern Sargasso Sea on the basis of direct current measurements obtained when the eddy moved by a current meter mooring. The temperature and flow field at 4012 m were both influenced by the passage of the eddy, with a cooling throughout the water column. Hydrographic measurements accompanied by direct measurements of little motion at 2000 m suggested a weak anticyclonic circulation in the deep water below 2000 m, but the direct current measurements at 4012 m could not be interpreted as showing the passage of an anticyclonic disturbance.

Since the temperature perturbations associated with Gulf Stream rings and isolated eddies have been seen at great depths, some of the warm events in the present data and in particular the noticeable temperature event in mid or late February 1976 might be associated with the passage of warm core rings. A U.S. National Weather Service analysis in *Gulfstream* (Anon., 1976) showed a 150 km diameter warm core ring at about 41.6N and 56.1N on 28 February 1976. The ring center was about 130 km northwest of westernmost Mooring 1 and 160 km from Mooring 4 on that date, and the temperature increases are most pronounced at the western moorings. This ring could not be seen in satellite imagery west of 55W at the end of March

1976, so it may have atypically moved eastward or it may have been reabsorbed in the Gulf Stream. Such satellite-derived analyses are only infrequently available as far east as 55W because of cloud cover.

The very large temperature increase during May and June 1976 appears to be associated with a surface movement of the Gulf Stream rather than any detached ring. Sea surface temperature maps in Figures 11a and b were adapted from experimental Gulf Stream analyses by the Environmental Products Group of the U.S. National Earth Satellite Service for 28 May 1976 and 6-7 July 1976. On the earlier date the Gulf Stream at 55W is south of 39N and far south of the current meter array. Hydrographic measurements from C.S.S. *Dawson* while replacing the Bedford Institute moorings between 4-7 June 1976 showed the 15°C isotherm to lie deeper than 600 m at all mooring sites, characteristic of a location south of the Gulf Stream. There is a reversal of the deep flow from southeast to northwest at Moorings 2, 3 and 4 in early June 1976 at about the time of maximum warming, and a subsequent return to southeast flow later in the month. A detailed look at the moored records from this period shows that both temperature and current events propagate westward through the array. The surface temperature map for 6-7 July 1976 in Figure 11b is the first such map available after 28 May 1976. It shows a large meander in the Gulf Stream just to the west of the array, oriented to the northwest and extending to about 41N. There is a southward meander centered at 39N and 59W that could have evolved from the meander south of the array on 28 May 1976, and the deep variability might be related to the transit of the surface Gulf Stream through the array which is inferred from the near-surface observations. There is not enough surface information available to critically test this possibility.

In the surface Gulf Stream, events that produce cold core eddies to the south of the Gulf Stream and warm core eddies to the north clearly transport heat northward across the Stream. If such eddies typically have a level of no motion near 2000 m with flow reversals in the deep water, and a temperature perturbation of the same sign throughout the water column, the sign of a velocity-temperature covariance would change across the level of no motion but the deep velocity-temperature covariance would still be related to the surface features. The deep eddy heat flux derived from the present measurements is directed just south of east. As emphasized by a reviewer, the depth contours in the vicinity of the array are oriented northwest to southeast and the direction of eddy heat flux is not significantly different from along the isobaths, nor is the mean flow direction nor the direction of the principal axis of current variance. The reviewer suggested a reasonable alternative explanation for the deep eddy heat flux, namely that it could be due to pulses of cold Western Boundary Undercurrent flow along the depth contours and so not be related to the surface motion of the Gulf Stream.

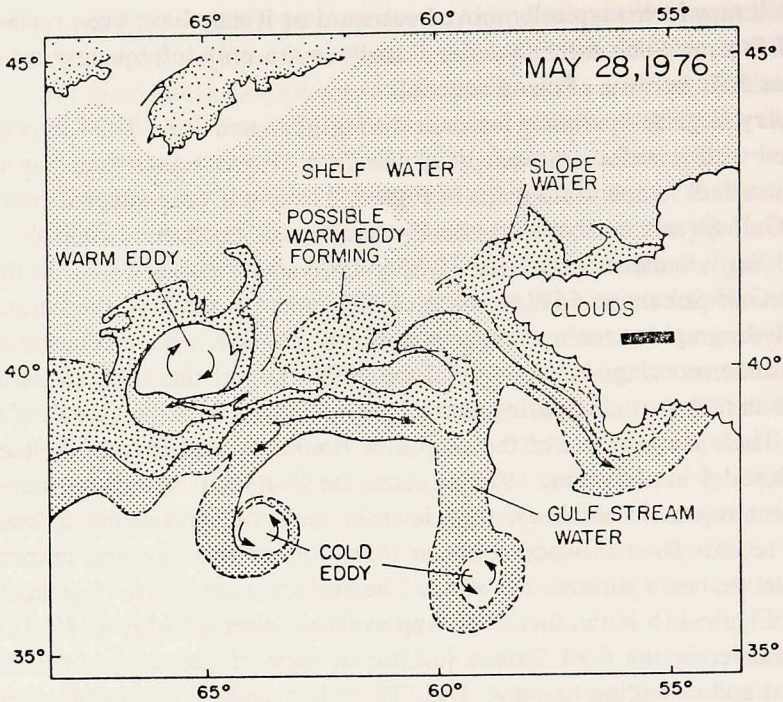McCartney *et al.* (1980) discuss a temperature section along 55W from R. V.

Figure 11a. Experimental Gulf Stream Analysis by the Environmental Products Group, U.S. National Earth Satellite Service, showing the surface temperature field in the vicinity of the Gulf Stream Array on 28 May 1976.

Knorr Cruise 60 during 3-18 October 1976 which gives the meridional structure of the deep temperature field at one time during the moored experiment. Near 4000 m the 2°C potential temperature contour in the *Knorr* section slopes downward to the south between 41N and 39N with a vertical excursion of about 400 m over the 220 km interval. At a constant depth of 4000 m the temperature increases by about 0.2°C from 41N to 39N. The meridional structure in the deep temperature field is congruent with variations at shallower levels up to and within the main thermocline, where the 10°C isotherm sinks from about 400 m at 41N to a maximum of 900 m at 39N. The surface Gulf Stream was found at 41N in the section. The vertical coherence of the meridional variations in temperature in this instance suggests that the zonal structure in the variability at 4000 m will be present to some extent, at least some of the time, in the mid and upper levels of the water column and especially at levels below the main thermocline. The deep velocity should be nearly geostrophic, based on a Rossby number of about 0.06 from a maximum speed of 0.5 ms^{-1} and a spatial scale of 90 km; accordingly, vertical shear in horizontal current must be balanced by horizontal density gradients. Since the horizontal den-
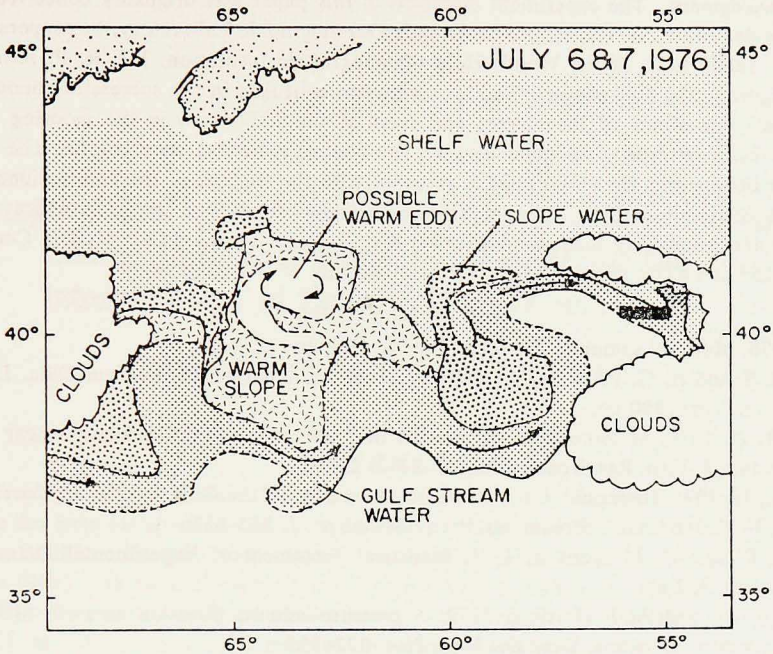
Figure 11b. The same for 6-7 July 1976.

sity gradients in the deep water are relatively small, the intense bursts of flow observed at 4000 m likely extend upward in the water column to at least 2000 m, although the present data offer no direct observations of vertical structure.

Meridional advection of the deep meridional temperature gradients such as seen in the *Knorr* 60 section probably accounts for some of the temperature variability at 4000 m. A characteristic speed scale of 0.1 ms^{-1} and a time scale of 30 days give a horizontal excursion of 250 km which is sufficient to advect the 0.2°C temperature differences associated with the deep front meridionally back and forth across the array. Since the meridional velocity component would be in quadrature with the temperature variations in such a reversible advective model, there would be no net eddy heat flux and the mechanism is not inconsistent with the observed small negative correlation between meridional velocity and temperature fluctuations.

The results of the Gulf Stream Experiment reveal considerable structure in the deep Gulf Stream at 55W, but certain unanswered questions remain and further work is needed. Specific areas for future experimental efforts include the investigation of the vertical structure of the mean flow and the eddies, a fuller description of the horizontal structure both at depth and in the upper layers, and an exploration of the possible relationship between thermocline variability and the small but significant eddy heat flux found in the deep water.

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