Moored velocity measurements on the edge of the Gulf-Stream recirculation

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ABSTRACT

Mean velocities, eddy kinetic energies and time series of velocities at several depths are presented from moored current meters for the 15 month period May 1978 to July 1979 as part of the POLYMODE Local Dynamics Experiment, centered at 31N, 69°30′W. The mean velocities in the upper one kilometer are toward the southwest at 2.4 to 4.4 cm/s, consistent with Worthington's (1976) description of the mean circulation of the North Atlantic. The abyssal flow is toward the east, directed toward shallower depths, at 2 cm/s. This deep flow agrees with neither Worthington's description nor other direct current measurements along 70W. The record-averaged eddy kinetic energies are three times as large as those 300 km to the south during the MODE experiment. For periods between 880 and 2 days the vertical structure of the kinetic energy spectrum is independent of frequency in contrast to the MODE results. These results are consistent with those obtained at other longitudes when position in the mean circulation (relative to the Gulf Stream) is taken into account, indicating that this rapid increase in kinetic energy and change of spectral vertical structure in the region of return flow compared to the "mid-ocean" may be ubiquitous.

Twice during the 15 month record strong surface intensified jets passed through the array and contribute substantially to the eddy kinetic energy. Averages excluding these two periods indicate, however, that the mesoscale eddies seen in between these events are still more energetic than those seen to the south. The abyssal flow is dominated, especially during the passage of the jets, by oscillatory flow consistent with the topographic Rossby wave description derived from the 1300 m SOFAR floats (Price and Rossby, 1982). In addition small scale eddies are apparent when the jets are present. Thus the rapid increase of eddy kinetic energy within the recirculation region appears, in part, to be associated with a different eddy structure.

1. Introduction

A nine mooring current meter array, centered at 31N, 69°30′W, was deployed for the fifteen month period from May 1978 to July 1979. These observations were part of a cooperative experiment, the POLYMODE Local Dynamics Experiment (LDE), which included a two-month intensive hydrographic survey, neutrally buoyant (SOFAR) floats, and vertical profiles of velocity. From the moored velocity measurements statistics have been computed to characterize the mean flow and low

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frequency (sub-inertial) variability. In addition, the velocity data is presented to demonstrate qualitatively the character of the eddy variability.

This array was part of a longer effort, encompassing the MODE, POLYGON, and POLYMODE experiments, to observe the low-frequency variability in the Atlantic subtropical gyre. Previous exploration (Schmitz, 1976, 1980; Luyten, 1977; Richman *et al.*, 1977) along 70W and other longitudes has shown a significant variation of eddy kinetic energy depending upon location within the mean circulation of the North Atlantic according to Worthington (1976). Mean velocities and eddy kinetic energies computed from the moored array are used to extend this description. Statistics averaged over the two-month intensive experiment are compared with the longer averages to place the shorter experiment in context of the "climatic" environment. It is shown that this two-month period was more energetic than the average, but that there were other periods during the 15 month deployment of similar mesoscale structure.

Series of snapshots of horizontal structure of velocities and series of velocities from several depths from one mooring are also presented. During the intensive experiment striking, smaller than expected spatial scale features in the hydrographic surveys (Taft *et al.*, 1978; Ebbesmeyer *et al.*, 1978), SOFAR float tracks (Rossby *et al.*, 1982) and in the vertical profiles of velocity (Sanford, 1978) also can be detected in the mooring velocity data. The character of the eddy field for the remainder of the 15-month deployment suggest that the intensive experiment may have been unusual, but not unique. The data further suggest that there is a change in eddy structure, as well as an increase in kinetic energy, from that observed in the MODE region, 300 km to the south.

The array configuration and its relationship to bottom topography is shown in Figure 1. The array was located on the flank of the Bermuda Rise. The Hatteras Abyssal Plain can be seen on the western side of Figure 1. The bottom slope computed from a least-square fit to the depths at the moorings is 1.3×10^{-3} oriented 91°T. If this slope is combined with the change of Coriolis parameter with latitude, $\beta = 2.0 \times 10^{-13}\text{sec}^{-1}\text{cm}^{-1}$, and the local depth, $H = 5.35$ km, the resulting contours of f/H (Coriolis parameter/local depth) will be oriented along 133°T with a cross contour gradient of $5.0 \times 10^{-19}\text{sec}^{-1}\text{cm}^{-2}$ along 43°T.

2. Statistics

Mean and eddy variances are computed for the velocity measurements over both the entire record length and the intensive two-month experiment. The record-length average values will be compared with both direct current (Schmitz, 1976, 1980; Richman *et al.*, 1977; Schmitz and Owens, 1979) and density (Worthington, 1976; Ebbesmeyer and Taft, 1979) observations. This serves both to define the structure

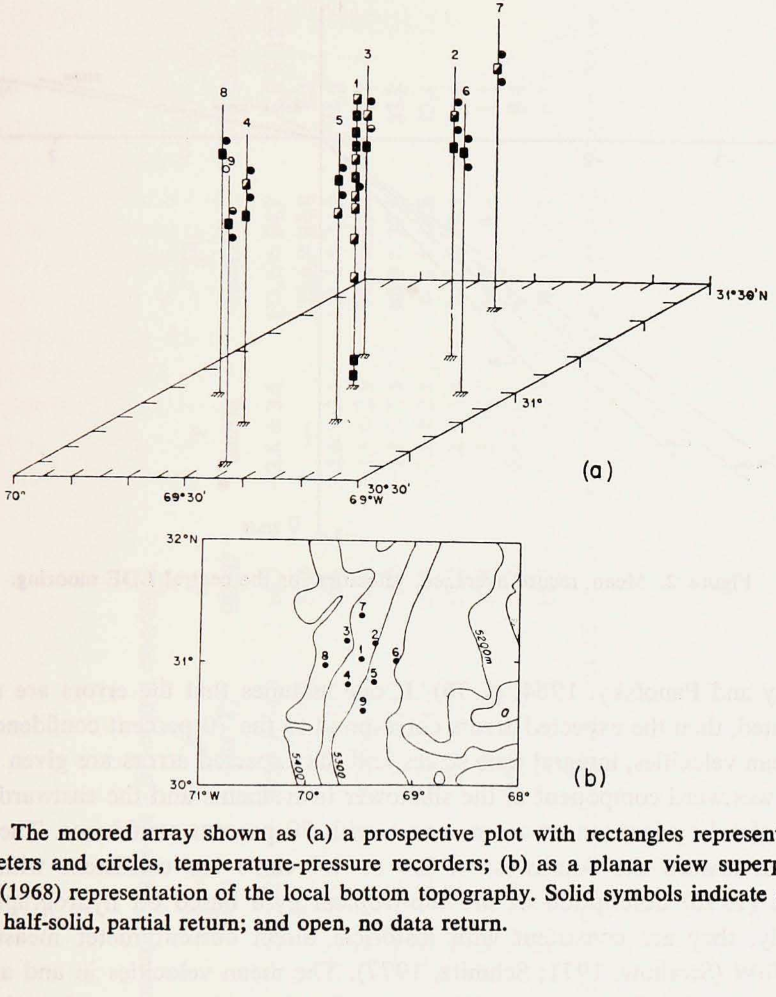


Figure 1. The moored array shown as (a) a prospective plot with rectangles representing current meters and circles, temperature-pressure recorders; (b) as a planar view superposed on Pratt's (1968) representation of the local bottom topography. Solid symbols indicate full data return; half-solid, partial return; and open, no data return.

in mean and eddy statistics along 70W and to determine the "typicality" of the intensive two-month observations.

The mean velocity vectors for the instruments on the central mooring are shown in Figure 2. Expected errors (estimates of the root mean squared differences between the computed and true values) in the computed statistics can be estimated from the velocity spectra as proposed by McWilliams and Flierl (1977). These error estimates take into account the shape of the spectra and the finite record length which are neglected by more traditional estimates based on overall moments. In the limit of long record lengths, T, McWilliams and Flierl have shown that their error estimates converge to those based on overall moments, for example the expected error for the mean which is estimated as $\sqrt{2\tau_I\, \sigma^2/T}$ where τ_I and σ^2 are the integral time scale of the auto-correlation function and the variance, respectively

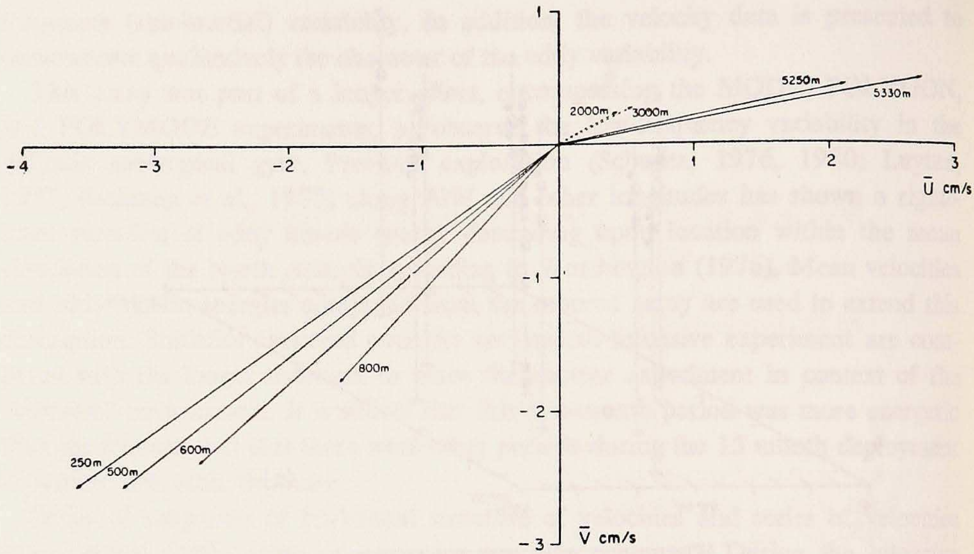


Figure 2. Mean, record averaged, velocities for the central LDE mooring.

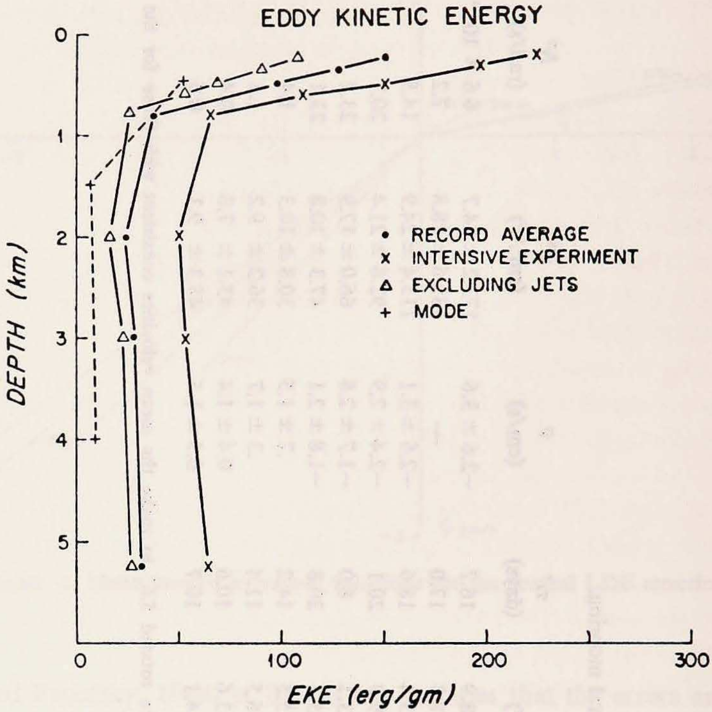
(Lumley and Panofsky, 1964, p. 36). If one assumes that the errors are normally distributed, then the expected errors correspond to the 70 percent confidence limits. The mean velocities, integral time scales and the expected errors are given in Table 1. The westward component at the shallower instruments and the eastward component at the deep instrument are non-zero with 70 percent confidence. The shallow velocities toward the Southwest at 2.4 to 4.4 cm/s are consistent with Worthington's (1976) description of the sub-tropical gyre based on hydrographic data. Similarly, they are consistent with historical direct current meter measurements along 70W (Swallow, 1971; Schmitz, 1977). The mean velocities in and above the main thermocline (in the top one kilometer of the ocean) are approximately aligned across f/H contours while those below the thermocline are directed upslope. The near bottom velocities are eastward which disagrees with both Worthington's (1976) deep gyre and direct current measurements along 70W (Swallow, 1971; Schmitz, 1977).

Unfortunately, instrument failures and loss of the redundant central mooring precludes continuing this description of the mean velocities to mid-depths. Shorter records were obtained at 2000 and 3000 m depth of 307 and 295 days, respectively. The means at these depths both were oriented toward 63°T with speeds of 0.51 and 0.62 cm/s, respectively. These have been plotted as dashed lines in Figure 2. Depth averaged velocities using those records longer than 290 days are $u = 0.10$ and $v = -0.35$ cm/s. These estimates are not significantly different from zero.

Table 1. Record averages, time scales, and estimated errors for LDE central mooring.

Record number	Duration (days)	Depth (meters)	τ_I^u (days)	$\bar{u}$ (cm/s)	$\overline{u'^2}$ (cm^2/s^2)	τ_I^v (days)	$\bar{v}$ (cm/s)	$\overline{v'^2}$ (cm^2/s^2)	N^2 $(rad/s)^2$
6401	445	250	7.3	−3.6 ± 2.6	129.5 ± 18.9	16.7	−2.6 ± 3.6	173.2 ± 34.7	6.6×10^{-6}
6402*	445	375	8.1	—	117.7 ± 18.3	17.0	—	139.6 ± 28.8	7.2
6403	445	500	8.3	−3.2 ± 1.8	84.6 ± 13.4	18.6	−2.6 ± 3.1	113.4 ± 24.9	14.5
6404	445	600	8.5	−2.7 ± 1.5	61.0 ± 9.9	20.1	−2.4 ± 2.9	92.6 ± 21.4	20.7
6405	138	700	8.5	−1.7 ± 2.3	45.0 ± 13.1	8.0	−1.7 ± 2.8	66.0 ± 17.9	23.2
6406	445	825	9.5	−1.6 ± 1.1	28.9 ± 15.1	20.8	−1.8 ± 2.1	47.3 ± 10.8	23.1
64010	309	2000	9.4	0.4 ± 1.3	18.3 ± 5.5	14.2	.2 ± 1.5	30.8 ± 10.3	1.4
64011	297	3000	11.0	0.6 ± 1.5	21.7 ± 6.5	11.4	.3 ± 1.7	36.2 ± 9.2	1.1
64012	445	5250	9.6	2.1 ± 0.9	20.2 ± 3.6	10.6	0.4 ± 1.4	43.1 ± 7.8	0.4
64014	445	5330	9.9	2.7 ± 1.0	23.1 ± 4.1	10.7	0.5 ± 1.5	48.3 ± 9.1	0.5

* This instrument had an incorrectly calibrated direction. The velocities were rotated 5.6° to make the mean velocities consistent with those for the instruments above and below it.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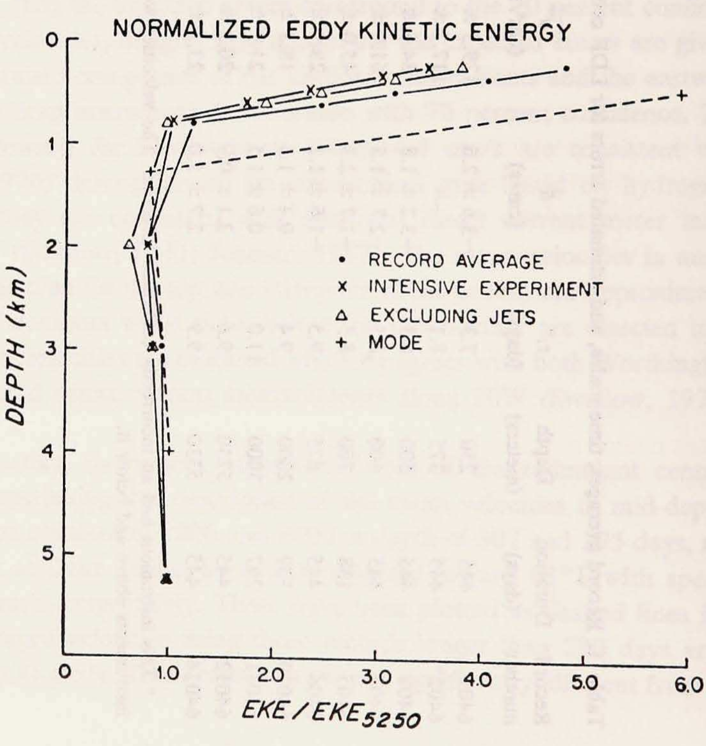
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Eddy kinetic energies (EKE), with mean velocities removed, are shown in Figure 3a for both averages over the entire record and over the two month intensive experiment. The intensive experiment occurred during a period of increased EKE when the deep energy was twice as large, while above the thermocline it increased only half again as much. From the velocity variances given in Table 1 it can be seen that these increases are larger than the expected errors for the record average EKE. The rapid increase in EKE in the upper kilometer is indicative of a significant baroclinic component. As we shall discuss in section 3, there were two periods of particularly energetic flow associated with strong surface intensified jets, one of which occurred during the intensive experiment. During the rest of the observation period the velocity field contains eddies of spatial structure (~ 100 km horizontal scale) similar to that observed in the MODE region. The EKE computed excluding the strong surface intensified jets still has more energy that was observed in the MODE region, as shown in Figure 3a.

To examine vertical structure in more detail, the ratios of EKE at a given depth to that at 5250 m (4000 m for MODE) have been plotted in Figure 3b. All three averages in the LDE region are less baroclinic than MODE. From the differences between the three averages one can see that the intensive experiment did not have a vertical structure different from most of the rest of the observation period. Only when the very energetic second baroclinic jet is included, does the average vertical structure become more baroclinic than that for the intensive experiment. To illustrate the contributions of the two periods of energetic flow to the record mean velocities, the mean velocities are plotted in Figure 4 for the three averaging intervals used to produce Figure 3. Since the surface intensified jets are in the same direction as the record mean velocities, the shallow mean velocities change magnitude, not sign, depending on the averaging interval used. The abyssal velocities during the periods in which the jets were present were not unidirectional, so that the different averaging intervals have greatly different means.

Schmitz (1978) has observed that in energetic regions associated with the Gulf Stream return flow the shape of the kinetic energy frequency spectrum is approximately independent of depth. Also, mesoscale eddy time scale processes (usually periods of 20-100 days) dominate the lower frequency secular time scales (periods of 150-1000 days) in both the thermocline and deep ocean in the Gulf Stream return flow. The spectral estimates from the LDE at 500 m and 5250 m, shown in Figure 5, show a similar behavior. This is in sharp contrast to the vertical structure observed in the lower energy, mid-ocean or interior regions such as MODE. In the

Figure 3. (a) Vertical variations of eddy kinetic energy (record mean velocities removed) for record averages; averages over 17 May to 17 July, 1978; for averages excluding 17 May to 17 July, 1978, and 20 April to 25 May, 1979; and for the MODE region. (b) Normalized vertical variation of eddy kinetic energy.

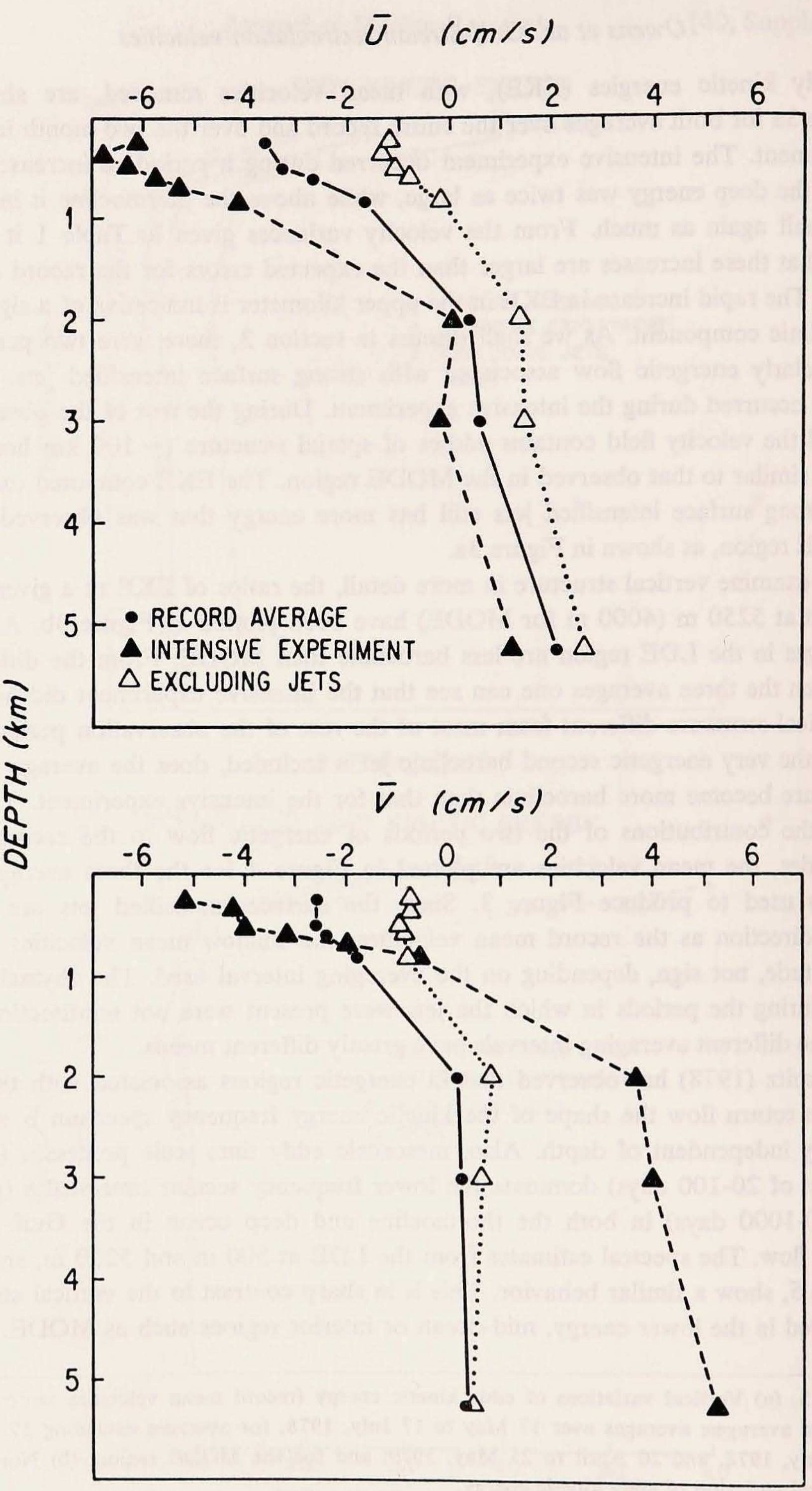

Figure 4. Mean velocities for the different averaging intervals given in Figure 3.

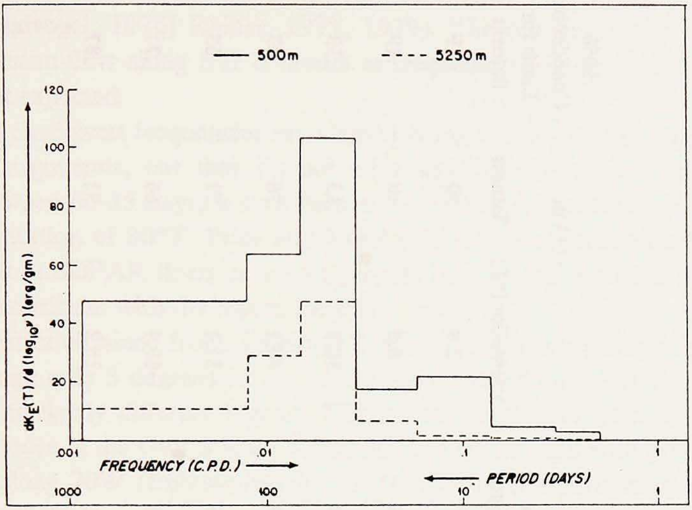

Figure 5. Estimates of the decadal frequency spectrum of eddy kinetic energy for 500 m and 5250 m on the LDE central mooring (31N, 69°30′W).

mid-ocean, the spectra in the thermocline are red with a similar shape as seen near the Gulf Stream. For the mid-ocean abyssal velocities, however, the secular scale is greatly reduced, and the spectrum is dominated by mesoscale eddy time scales [see Figures 3 and 4 in Schmitz (1978)]. Thus the LDE region is similar to other locations within the Gulf Stream return flow system since the kinetic energy spectra are independent of depth.

The velocity variance and covariance spectra can be represented in a form which is invariant under coordinate transformations using the principal axes (Fofonoff, 1969). The degree of rectilinear polarization or wave-like character can be estimated by computing an ellipse flatness, the ratio of the semi-minor to semi-major components of the ellipses,

$$F = \frac{E - R}{E + R}$$

where $E = \frac{1}{2}(S_{uu} + S_{vv})$, $R^2 = \frac{1}{4}(S_{uu} - S_{vv})^2 + S^2_{uv}$, S_{uu} and S_{vv} are the velocity spectra, and S_{uv} is the velocity covariance. F is invariant under coordinate transformations and is a ratio of chi-squared random variables which are independent under the null hypothesis, so that F has an F-distribution (Thompson, 1977). Thus, for significant rectilinear flow, F should have a value below the confidence limit derived from F-test criterion. The spectral decomposition into various bands for the kinetic energy, orientation of the axes, and flatness at the 500 m and 5250 m depths are shown in Table 2.

Table 2

Period range (days)	500 m K_E (erg/gm)	500 m orientation(°T)	500 m flatness	5250 m K_E (erg/gm)	5250 m orientation(°T)	5250 m flatness	90% Confidence limits for flatness
Band 1 880-126	40.0	25.3	.15	8.5	2.8	.30	.19
Band 2 126-68	16.9	18.5	.12	7.6	8.8	.48	.19
Band 3 68-35	29.1	13.0	.27	13.3	30.3	.13	.33
Band 4 35-17	5.2	35.0	.77	1.9	40.1	.76	.47
Band 5 17-7.3	8.0	−45.9	.56	0.5	−31.1	.51	.63
Band 6 7.3-3.4	1.4	−25.5	.69	0.3	−69.4	.66	.71
Band 7 3.4-2	0.6	−64.6	.76	0.1	28.2	.91	.87

At 500 m six of the seven bands, all but the center of the mesoscale, show significant rectilinear character [$F < F_o(90\%)$]. At low frequencies the major axis is directed along the mean flow and across contours of f/H. These results at low frequencies contradict predictions by β-plane turbulence over topography (Bretherton and Haidvogel, 1976; Rhines, 1977, 1979). The rectilinear character aligned across the mean flow along f/H contours at frequencies higher than the mesoscale was also not expected.

At depth the lowest frequencies are aligned along depth contours as predicted by turbulence arguments, but they do not have significant flatness. The band, with periods between 68-35 days, with a flatness below the 90 percent confidence limit has an orientation of 30°T. Price and Rossby (1982) have interpreted the motion of the 1300 m SOFAR floats as a topographic Rossby wave whose direction and period are consistent with the results for this band.

The statistics obtained from the moored current meter array show that the LDE area, although only 3 degrees of latitude to the north of the MODE area, appears to be in a markedly different regime. This is consistent with both observations at other longitudes in the Gulf Stream—recirculation system and with potential energy variations along 70W (Ebbesmeyer and Taft, 1979). Comparison of the statistics averaged over the shorter, two-month intensive experiment with those for the entire fifteen-month deployment indicate that it was one of two periods of particularly energetic flow.

3. Qualitative flavor of the eddy variability

The change from the MODE region in spatial structure of the mesoscale variability discussed above was resolved by the moored array and will be the subject of subsequent statistical analyses. As some of the other observations from the intensive experiment have been reported (Taft *et al.*, 1978; Ebbesmeyer *et al.*, 1978; Sanford, 1978; Rossby *et al.*, 1982, it is appropriate here to discuss qualitatively the spatial structure of the eddy field during that period, and its relationship to the longer term moored experiment. A quantitative analysis of the spatial structure observed by this current meter array will appear elsewhere. In this section our intent is to give the reader a qualitative view of the eddy variability seen in the LDE.

The original time series have been low-passed using a running mean Gaussian filter with a 24 hr half-width to remove variability associated with inertial, tidal, and higher frequency processes. The resultant series is subsampled once a day. The horizontal spatial structure is presented in a sequence of daily snapshots of the current vectors at 600 m, Figure 6. The vertical structure is shown in the vector time series for the central mooring, Figure 7.

During the intensive experiment (17 May to 17 July, 1978), three energetic small-scale eddies and a mesoscale jet associated with a density front in the upper thermocline have been identified and described by Taft *et al.* (1978); Ebbesmeyer *et al.* (1978); Sanford (1978); and Rossby *et al.* (1982). Two of the three eddies and the mesoscale jet have clear signatures in the moored velocity records. The

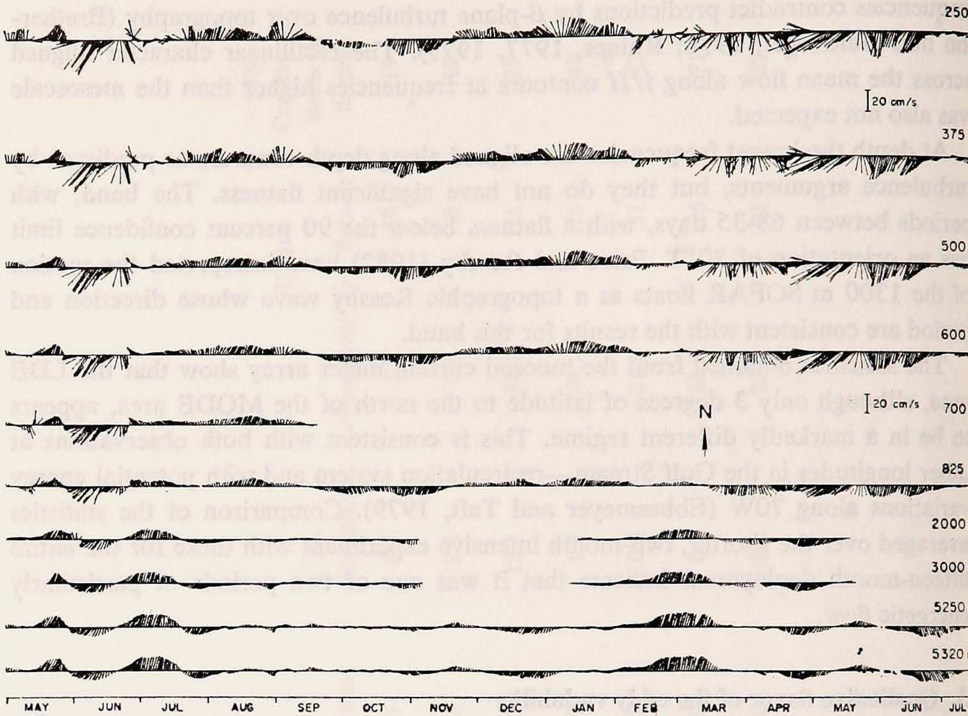

Figure 7. Vector time series of the low-frequency data from the central mooring located at 31N, 69°30′W.

third small scale eddy cannot be seen due to its small horizontal scale, 25 km diameter, and the large advective velocity, 30 cm/s, in which it is embedded. This small-scale eddy so clearly seen in the SOFAR float trajectories (Rossby *et al.*, 1982) cannot be seen in the low-passed time series shown here although it did pass close to moorings 1, 2, 3, 7, and 8.

The first event in the sequence of snapshots is the appearance of a mesoscale jet with southwestward velocities of 30 cm/s which enters the array at the end of May and drifts toward the northwest. The northwestern flank of the jet moves through the array at approximately 4 cm/s. The cross-stream half-width of the jet is approximately 50 km while the downstream scale is unresolved by either the moored array or the density survey grid (Taft *et al.*, 1978; Ebbesmeyer *et al.*, 1978) and thus is longer than 200 km. The temperature gradient associated with the jet is the strongest observed in the composite US-USSR XBT surveys (Metcalf, Baranov *et al.*, 1979). The vertical structure during the passage of the mesoscale jet through the array appears to be complicated (Fig. 7). For two weeks before the appearance of the jet at the central mooring, there is a large, 15 cm/s, barotropic flow to the north-northeast. If one were to focus only on the velocities below the thermocline, the period from 15 May to 10 August, 1979 which brackets the appearance of the jet shows the passage of a wave-like phenomenon with oscillations across f/H contours. This is consistent with an analysis of the 1300 m SOFAR floats by Price and Rossby (1982) who found that the very coherent motion of the floats during this period could be described as a topographic-planetary Rossby wave. However, from the current vectors shown in Figure 7, it is apparent that this phenomenon is more complicated than a simple plane wave. The first half cycle is barotropic in that the shallow velocities are visually coherent with those just above the bottom. The second cycle cannot be separated from the surface intensified jet which overlies it. The last two cycles appear to be bottom intensified in that the shallow velocities appear to have no relationship to the abyssal ones. Figure 7 also suggests that either there is a second frequency present or that the frequency varies significantly over one wave period.

Embedded in the mesoscale jet was a deep thermocline eddy which was extensively examined by the density surveys (Taft *et al.*, 1978) and by free-falling, velocity profiles (Sanford, 1978). This small-scale eddy was a lens of anomalous water with a limited vertical extent. This can be seen in the velocity time series from the central mooring. For the period 29 May to 8 June, 1978, which is just after the passage of the barotropic event, there is no appreciable shear between the 800 m and 3000 m velocities. At the same time the velocities at 2000 m showed a 360° rotation as the eddy passes by the central mooring. Thus, the velocity time series substantiate the vertical confinement of this small scale eddy.

During the second half of the intensive experiment a small scale eddy is advected along the southeastern flank of the jet. It is first evident as a closed circulation in the 600 m array on 25 June and moves quite rapidly, ~ 20 cm/s to the southwest. The trailing edge of this eddy has a considerably larger horizontal scale than the leading edge which is in close proximity to the jet. Furthermore, this scale is much larger than that seen in the density data, 20 km (Ebbesmeyer *et al.*, 1978).

While the intensive experiment was dominated by the mesoscale jet and the small scale eddies, most of the sequence of snapshots of velocities at 600 m is characterized by mesoscale eddies with dominant scales somewhat larger than the array which drift through the array toward the west. This was the anticipated structure based on the results of the MODE experiment. In addition there does not appear to be any energetic small scale eddies associated with these mesoscale eddies.

In May 1979, another intense mesoscale jet, with even stronger velocities than were seen in the intensive experiment, passed through the LDE area. One can only speculate on the occurrence of these two jets in late spring/early summer. Perhaps this is a nearly annual cycle, but two observations are insufficient to be specific. This second jet also has enhanced small scale eddy energy associated with it. Before the jet passes through the array, 5-15 April, 1979, a small scale eddy can be seen in the velocity records. It thus appears that the energetic small scale eddies may be associated with the mesoscale jets, but there is still a reduced activity at these scales in intervening periods.

The strong abyssal oscillations seen in the intensive experiment appear at several other parts of the record, most noticeably in February-March 1979 and June-July 1979. These observations in which the abyssal flow is associated with topographic effects, while the upper part of the ocean responds in a more chaotic mesoscale eddy behavior have also been seen in numerical simulations of mesoscale eddies (Owens, 1979).

4. Conclusions

The mean velocities and eddy kinetic energies for the LDE area are used to extend the description of their variations along 70W. The mean velocities above 1 km depth, are consistent with the general circulation deduced from hydrographic data by Worthington (1976). The abyssal means are opposed to those described by Worthington, and directed across bottom contours indicating upslope flow.

The eddy kinetic energy has trebled in going from the MODE area, 28N to the LDE area 31N. This change mirrors that for potential energy calculated from historical data by Ebbesmeyer and Taft (1979). The vertical distribution of the kinetic energy in the lowest frequency band (for the LDE data at period of 888 days to 126 days) does not vary from those for the higher frequency bands. This again is in contrast to the MODE results where the lowest frequency band is much more surface intensified. This variation along 70W is consistent with that seen along 55W (Schmitz, 1978) if one compares similar locations with respect to the general circulation pattern described by Worthington (1976). When decomposed in principal axes, the velocity variance in the lowest frequency bands is aligned across contours of f/H in the thermocline and along bathymetry near the bottom. The band containing the largest energy per band width, with periods between 68 and 35 days, has a very small flatness at depth and an orientation consistent with the topographic Rossby wave fit to the six month SOFAR float tracks at 1300 m (Price and Rossby, 1982). The statistics based solely on the two-month intensive experiment show it to be significantly more energetic than the average.

This increased energetic flow during the intensive experiment is quite evident in the velocity time series. The two striking features in the plots of horizontal velocities at 600 m during the intensive experiment are the northwestward drift of the surface intensified jet with velocities toward the southwest and a small scale eddy on the southeastern flank of the jet with horizontal scales as large as the mooring array. These features are also seen in the density survey (Taft *et al.*, 1978; Ebbesmeyer *et al.*, 1978), but the eddy appears to have a shorter horizontal scale in the density field. The abyssal velocity time series are consistent with the topographic

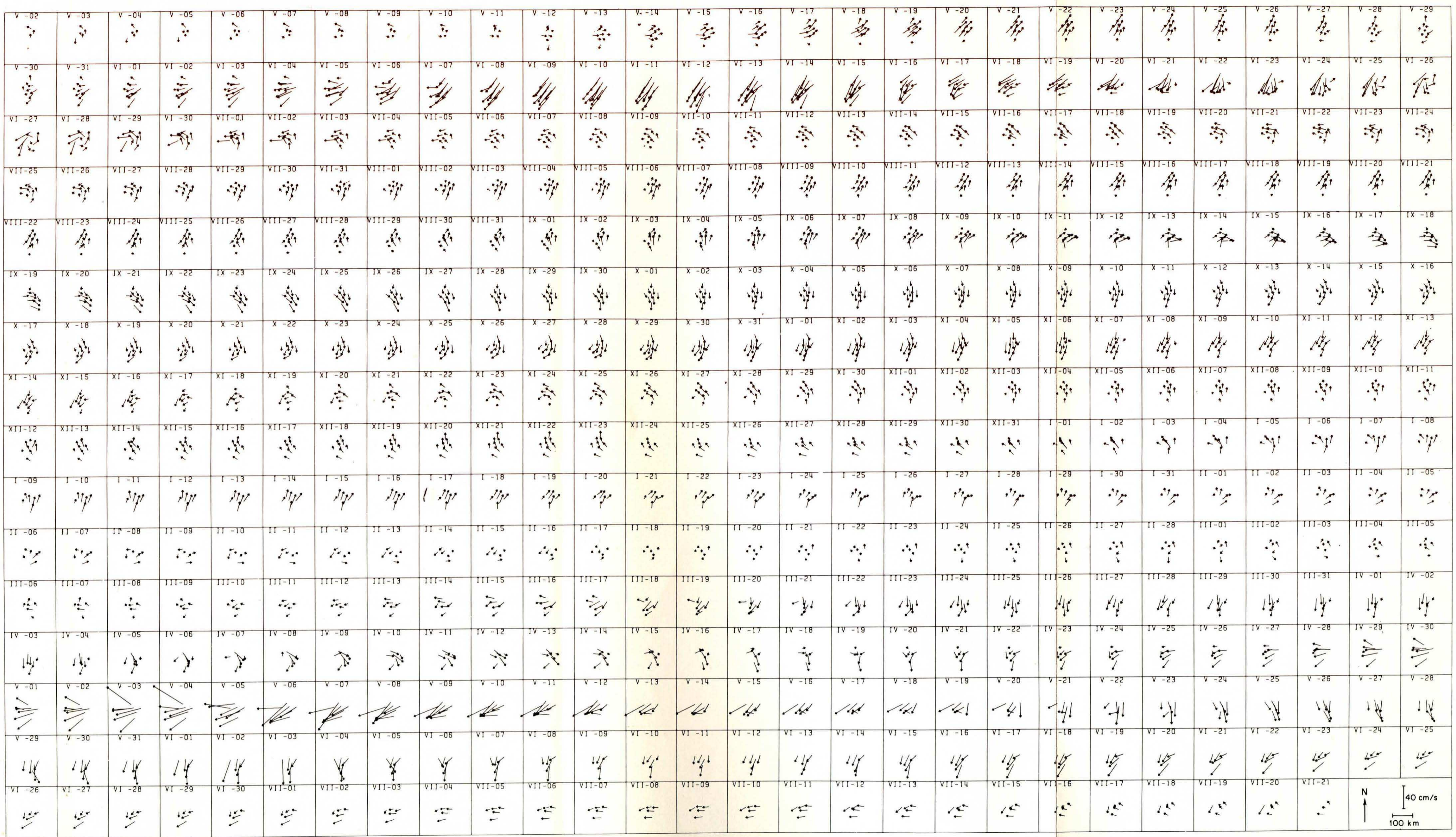

Figure 6. Array representation of low-frequency currents at 600 m depth for the entire 15-month deployment from 2 May 1978 (V-02) to 21 July 1979 (VII-21). Central mooring is located at 31N, 69°30′W.

Rossby wave fit for the 1300 m SOFAR float tracks. Furthermore, there are other instances of similar abyssal oscillations during the 15-month time series.

Although the period during which the intensive experiment took place was significantly more energetic than the 15-month average, it was not uniquely so. There were two periods dominated by large amplitude baroclinic jets, one during the intensive experiment and another stronger one in May 1979, with small scale eddies apparently associated with them. The intervening times have eddies propagating through the array which more closely resemble those seen in the MODE region with only hints of small amplitude small-scale eddies.

Thus, the LDE region, 31N, 70W appears to be within the southern extent of the Gulf Stream recirculation according to Worthington (1976). There is a marked increase in eddy energy over that to the south outside of the recirculation which is also observed at other longitudes (Schmitz, 1976, 1978). In this case, this increase is also associated with a change in the spatial structure of the eddy variability.

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REFERENCES

Bretherton, Francis P. and D. Haidvogel. 1976. Two-dimensional turbulence above topography. J. Fluid Mech., *78*, 129–154.

Bryden, Harry L. 1976. Horizontal advection of temperature for low-frequency motions. Deep-Sea Res., *23*, 1165–1174.

Ebbesmeyer, Curtis C., Bruce A. Taft, Jeff Cox, James C. McWilliams, W. Brechner Owens, Myron Sayles, and Colin Shen. 1978. Preliminary maps from the POLYMODE Local Dynamics Experiment—second half. POLYMODE News, No. 54 (Unpublished manuscript).

Ebbesmeyer, Curtis C. and Bruce A. Taft. 1979. Variability of potential energy, dynamic height and salinity in the main pycnocline of the western North Atlantic. J. Phys. Oceanogr., *9*, 1073–1089.

Flierl, Glenn R. and James C. McWilliams. 1977. On the sampling requirements for measuring moments of eddy variability. J. Mar. Res., *35*, 797–820.

Fofonoff, N. P. 1969. Spectral characteristics of internal waves in the ocean. Deep-Sea Res., *16*, 59–71.

Lumley, J. L. and H. A. Panofsky. 1964. The Structure of Atmospheric Turbulence. Interscience, New York, 239 pp.

Metcalf, William G., E. Baranov *et al.* 1979. POLYMODE synoptic XBT mapping. POLYMODE News, No. 64. (Unpublished manuscript).

Owens, W. Brechner. 1979. Simulated dynamic balances for mid-ocean mesoscale eddies. J. Phys. Oceanogr., *9*, 337–359.

Pratt, Richard M. 1968. Atlantic continental shelf and slope of the United States—physiography and sediments of the deep-sea basin. Geological Survey Professional Paper 529-B, U.S. Government Printing Office, Plate 1.

Price, J. F. and H. T. Rossby. 1982. Observations of a barotropic planetary/topographic wave. J. Mar. Res., *40* (Supp.), 543–558.

Rhines, Peter B. 1977. The dynamics of unsteady currents, *in* The Sea, Vol. VI, E. D. Goldberg, ed., John Wiley & Sons, Inc., New York, 189–318.

—— 1979. Geostrophic turbulence. Ann. Rev. Fluid Mech., *11*, 401–441.

Richman, James G., Carl Wunsch and Nelson G. Hogg. 1977. Space and time scales of mesoscale motions in the Western North Atlantic. Rev. Geophys. Space Phys., *15*, 385–420.

Rossby, H. Thomas, Stephen C. Riser and Scott E. McDowell. 1982. On the origin and structure of a small-scale lens of water observed in the North Atlantic thermocline (in preparation).

Sanford, Thomas B. 1978. *Oceanus* 47 cruise report and preliminary scientific results. POLYMODE News, No. 51. (Unpublished manuscript).

Schmitz, William J., Jr. 1976. Eddy kinetic energy in the deep western North Atlantic. J. Geophys. Res., *81*, 4981–4982.

—— 1977. On the deep general circulation in the Western North Pacific. 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, William J., Jr. and W. Brechner Owens. 1979. Observed and numerically simulated kinetic energies for MODE eddies. J. Phys. Oceanogr., *9*, 1294–1297.

Swallow, John C. 1971. The Aries current measurements in the western North Atlantic. Phil. Trans. Royal Soc. London, Series A, *270*, 451–460.

Taft, Bruce A., Curtis C. Ebbesmeyer, James C. McWilliams, Myron Sayles and Colin Shen. 1978. LDE density program—first half. POLYMODE News, No. 51. (Unpublished manuscript).

Thompson, R. O. R. Y. 1977. Observations of Rossby waves near site D. Prog. in Oceanogr., *7*, 135–162.

Worthington, L. V. 1976. On the North Atlantic Circulation. Johns Hopkins Oceanographic Studies, *6*, 110 pp.

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