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Observations of mesoscale variability in the western North Atlantic: A comparative study

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ABSTRACT

As part of the POLYMODE experiment, three clusters (labeled A, B, C) of moored current meters and temperature-pressure recorders were deployed in three relatively unexplored regions in the North Atlantic Ocean to study the mesoscale variability. Clusters A (28N, 48W) and B (27N, 41W) were set on the western and the eastern flanks of the Mid-Atlantic Ridge, respectively, while Cluster C (16N, 54W) was set in the region of the North Equatorial Current. The cluster records were one year long, May 1977 to May 1978. Two site moorings were in place at A and B from May 1978 to September 1979.

In all three clusters, an 'eddy-containing' band with periods about 100 days was identified in the spectra of both temperature and velocity. In this band, eddy motion is dominated by its meridional component. At longer periods, zonal fluctuations become dominant and this zonal dominance is more pronounced in B and C than in A. At shorter periods, velocity fluctuations then become more or less isotropic. In general, the eddy energy is comparable to that found in the MODE area except at the 4000 m levels in Clusters A and B, where the eddy motion was greatly suppressed, presumably because of the presence of very rough topography. Over rough topography we find short period motions (≈ 10 days) in the deep water. Eddy length scales in all three clusters are comparable to those of the MODE eddies, whereas eddy time scales are larger in A and B and somewhat smaller in C. The vertical structure of the vertical displacement in A is dominated by a single baroclinic mode while it has more complex structures in B and C. The eddy velocity fields in A and B are coherent and in phase between 200 m and 1500 m and those in C are coherent through the water column with indications of marginal vertical phase propagation. Horizontal correlation calculations suggest that a westward phase propagation with a speed of a few kilometers per day exists in all three clusters. Some subtle differences have been found between A and B: eddy time scales are generally larger and kinetic energies slightly larger in B, and the influence of the Mediterranean water at mid-depths is more pronounced in B. There is no convincing evidence of horizontally uniform, potential energy conversion to kinetic energy in the region of Cluster C as suggested by some previous theoretical work.

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1. Introduction

The purpose of this paper is to describe some features of mesoscale variability in the North Atlantic Ocean as measured by three clusters of moorings set under POLYMODE (an amalgam of the USSR program POLYGON, and the US program MODE). The MODE experiment of 1973, as described by the MODE Group (1978) (Freeland et al., 1975, Richman et al., 1977, and McWilliams, 1976) was the first quantitative attempt to determine the nature and dynamics of the mesoscale in the western North Atlantic. The most important result of that experiment was perhaps a qualitative one: that an energetic variability on the mesoscale did exist and could actually be mapped in comparatively simple ways.

In POLYMODE, much of the observational work on mesoscale variability in the Atlantic went in two distinct directions. First, there was an attempt to increase the understanding of the detailed local dynamical balances in comparatively small regions which encompass one, or at most, a few mesoscale features. An example of a question under study is the balance of terms in the local vorticity equation as a function of the eddy energy. This portion of POLYMODE is called the "Local Dynamics Experiment" and is described by McWilliams and Heinmiller (1978).

The other major focus of POLYMODE may be best explained by listing some of the descriptive questions remaining at the end of MODE. MODE displayed a single dominant feature, an "eddy" with a diameter of about 200 km, having a comparatively simple vertical structure dominated by a barotropic and first baroclinic mode (even though they appeared coupled nonlinearly to some extent) which moved through the observational area during the lifetime of the observational program (3.5 months). We then wished to know: (a) whether such eddies were present all the time or only appeared intermittently; (b) whether larger and smaller scale features with longer lifetimes were present simultaneously but were not very visible because of the particular observational strategy; and (c) whether eddies tend to be isolated features, or occurred more or less uniformly and "tightly packed." In the MODE area most of these questions could be reduced to a single statistical problem of finding the spectrum of motion as a function of depth.

There was also the question of whether the MODE area (28N, 70W) was typical of the entire Atlantic. An exploration of the eddy kinetic energy levels along 70W meridian by the Moored Array Group at Woods Hole Oceanographic Institution, using single mooring sites (see Schmitz, 1976), suggested a rapid increase in energy levels toward the Gulf Stream. However, it was not possible to determine whether for example, the character of the variability apart from its intensity changed in any significant way, or whether the energy changes were linked purely with proximity to the Gulf Stream or were also related to topography, distance to the western boundary or to changes in atmospheric forcing.

In an effort to answer many of these questions, POLYMODE embarked upon a series of "statistical-geographical" experiments whose major goal was to quantita-
Figure 1. Location of the POLYMODE moored arrays and general bathymetry. L for Local Dynamics Experiment; M for MODE; I and II for Array I and II; A, B, and C for Array III Cluster A, B, and C.

tively measure and describe rather simple statistical and kinematical properties of the mesoscale variability in the North Atlantic.

Three moored arrays were deployed and are shown in Figure 1. The first, originally called the post-MODE array, was subsequently relabeled POLYMODE Array I. The moorings were in position for nine months, and a first picture was obtained of the geographical variability on short time scales, both as a function of topography and proximity to the boundaries and Gulf Stream. Data from this array are discussed by Richman et al. (1977) and Schmitz (1977, 1978).

POLYMODE Array II was in place for two years and is described by Schmitz (1978, 1980); it was deployed in the region near the Gulf Stream. Basic statistics of the mesoscale were obtained in the highly energetic regions south of the Stream and a recirculation of that current was directly measured (see Worthington, 1976; Stommel et al., 1978; Wunsch and Grant, 1982).

POLYMODE Array III, the focus of this paper, had as a primary motivation the direct measurement of low-frequency variability of vast unexplored regions of the North Atlantic where, because of dynamical reasons, qualitative changes in characteristics of the mesoscale were possible. It was set as three distinct clusters, labeled
A, B, and C in locations displayed in Figure 1. The specific choices of regions were determined as follows. Cluster A was set on the western flank of the Mid-Atlantic Ridge to explore the effects of very rough topography, and at the same time was set south of the Gulf Stream recirculation and to the southward extent of Array II. Cluster B was intended to explore the eastern basin of the North Atlantic, i.e., east of the Mid-Atlantic Ridge; it was also set on the flank of the ridge to determine whether a deep western intensification of the eastern basin flow occurs. Clusters A and B are only 400 km apart at approximately the same latitude, but we will see below that there are real differences between them.

Cluster C was set in another largely unexplored region: the North Equatorial Current on the northwestern extension of the Demerara abyssal plain. The very intense eddy activity south of the Gulf Stream suggested that large scale baroclinic flows could generate mesoscale variability through baroclinic, barotropic, or mixed instabilities. The upper portion of the Gulf Stream is too energetic to be adequately instrumented by moorings to determine directly the energy conversion mechanisms that might be operating, much less obtain quantitative information on their rates. The North Equatorial Current, while considerably weaker in velocity than the Gulf Stream, was suggested by Gill et al. (1974) as a potentially significant source of baroclinic generation of eddies through direct instability.

Underlying all of these choices of deployment areas, the objective was to increase knowledge of the time average flows to the extent that these are determinable from a few years of mooring deployments.

2. The experiment

The large scale topographic features at Clusters A, B, and C are shown in Figure 1. (This bathymetry is a smoothed version of Uchupi (1971) and was provided by Dr. K. O. Emery.) The mean bottom depth at the moorings in Cluster A is 4959 m, at B—4303 m, and at C—5336 m. Figure 2 displays the location of each mooring within the rather complicated topographic features that are shown on the Naval Oceanographic Office Charts NA 9-9A and NA-10. The U.S. Naval cartographers who draw these maps tell us that considerable artistic license is used in the construction of individual features on the maps. During mooring deployments we discovered new and different individual features in all these areas: both ridges (or mountains) and troughs. Our general impression is that on these maps, the maximum excursions of the topography in Clusters A and B area are fairly representative (5600 m to 3600 m in Cluster A and 4200 m to 3200 m in Cluster B), although the extreme topographic roughness on the horizontal scale of 1-10 km is not resolved. The Cluster C map shows smooth abyssal plain areas; but we did discover a few mountains which rise up to 1400 m above this plain and these do not appear on this map. B. C. Heezen and M. Tharp’s rendering of the “World Ocean Floor” (Lamont-
Doherty Geological Observatory, 1977) provides a better impression of the mountains in the Cluster C area. On the horizontal scale of the mooring elements, Clusters A and B are in “very rough” topographic areas because many protuberances can occur between moorings. Cluster C is in a nearly smooth area, because an abyssal plain covers most of the cluster area. These somewhat detailed maps of the mooring area are essential for subsequent discussions of deep currents.

All three clusters were deployed on conventional stiff, jacketed-wire, subsurface moorings with distributed buoyancy. The moorings were designed for a maximum 15° tilt for currents less than 50 cm/sec in the upper 500 m (nominally 2000 pounds tension in the line). This was the first time the POLYMODE program obtained year-long records in the North Atlantic above 500 m levels from subsurface moorings. The hydrostatic pressure (or depth) of various elements in the clusters was monitored by pressure sensors both in the temperature-pressure (TP) recorders and vector averaging current meters (VACMs). The r.m.s. vertical excursion of the moorings was a few meters, with the maximum excursion at A, B, C of 16 m, 17 m, 14 m, respectively. Because of the vertical stability of these moorings, no depth correction was applied to the data. The instruments nearest to the euphotic zone were on Cluster C at the 180 m level. After 353 days in water the sensor areas were free of biological fouling, although a few “barnacles” were found attached to instrument cases or flotation. There was no evidence of deposits on rotor bearings nor was rotor sticking observed on the records. Details of the individual instrument performance and mooring configurations are in the preliminary data reports (Koblinsky et al., 1979; Fu and Wunsch, 1979).

3. Hydrography and large scale dynamic topography

a. T-S characteristics. During the deployment cruise, CTD casts were made to the bottom at each mooring site at A and B and during recovery at all three clusters. The T-S diagrams at each cluster and instrument locations are indicated in Figure 3. Using these diagrams, we will try to place the clusters and instruments in the context of the North Atlantic water masses.

In all clusters the main thermocline lies between 20°C and 8°C and is of similar T-S characteristics. At Cluster C there is a fresh, warm water layer above 50 m which can be traced to overflow of surface water of the equatorial rain belt and may at times contain isolated layers of Amazon River water (Mazeika, 1973). At both Clusters A and B the relative salt maximum water from the Mediterranean outflow lies between 8°C and 5°C.

The behavior of the Mediterranean salt tongue is peculiar as it crosses the apex of the ridge. Katz (1970) pointed out a discontinuity in the T-S properties across the ridge, a finding confirmed by Joyce (1981). Note in Figure 3b the separation of the T-S curve of station 49 (corresponding to the southernmost mooring, 627, of Cluster
Figure 2. Local bathymetry, mooring locations and mean current vectors of the three clusters of Array III, drawn on NAVOCEANO maps.

B). The boundary of the salt tongue is remarkably abrupt; this may be significant in view of the mean velocities described below. At Cluster C and mooring 627 (station 49) of Cluster B, the salinity minimum at 6°C is characteristic of water in the intermediate levels of the South Atlantic or Antarctic. Station 1 in Cluster C is taken at the northernmost mooring, 79. The bottom instruments of Clusters A and B are in the North Atlantic Deep Water while the bottom 1500 m of water at C is clearly of Antarctic Bottom Water origin (see insert on Fig. 3c).

Notice the variable character of the T-S diagram at Cluster B compared to Clusters C and A. Near the surface in this cluster, and at 700-1500 m, the individual T-S dia-
grams show a signature which is typical of interleaving of water masses. Individual traces of salinity as a function of depth show that in the main thermocline (in Cluster C too) there is considerable vertical layering, while the T-S variability above and below the thermocline is more likely due to interleaving. Apparently, the water masses above 300 m and within the Mediterranean outflow are broken up or patchy on the horizontal scale of Clusters A and B; hence the temperature variability at these levels may not be a reliable measure of density.

b. Historical density field and the mean currents. To display the horizontal structure of the main thermocline density field in Array III area we edited the archived bottle data from the National Oceanographic Data Center. These values of $\sigma_t$ (and other parameters) were interpolated with splines onto a standard $1^\circ \times 1^\circ$ grid, smoothed with a Laplacian filter, and then contoured. Figures 4a and 4b display the distributions at 300 m and 700 m, respectively.

The principal features of the geostrophically balanced vertical shear of horizontal
Figure 4. The $\sigma_t$ field at three different depths along with the observed mean shear. (a) $\sigma_t$ at 300 m. 2441 stations were used. Also shown is the observed mean shear between 180 and 500 m at Cluster C. (b) $\sigma_t$ at 700 m. 2096 stations were used. The observed mean shears between 200 m and 1500 m at Clusters A and B are also shown.

currents of the subtropical North Atlantic are displayed in these figures. Figure 4a shows contours of $\sigma_t$ at 300 m. The vector at Cluster C is the difference vector between observed mean velocities at 180 m and 500 m (see Fig. 2 and Table 1a for mean velocity vectors). Using the vertically integrated thermal wind relationship we computed the horizontal velocity difference. (To obtain in situ horizontal density gradients for this computation a least square fit of a sloping plane was made to the in situ density distribution in an area of $4^\circ \times 4^\circ$ grid around Cluster C.) The results are shown in Table 1b.

Figure 4b shows contours of $\sigma_t$ at 700 m. The horizontal gradients of density have decreased in magnitude and are displaced to the north with the overall deepening of the main thermocline. Observed mean velocity differences between 200 m and 1500 m are shown as vectors at Clusters A and B, computed from cluster averages.
of the velocity at each level. Here, geostrophically derived velocity differences were also calculated using the plane fitting procedure within $6^\circ \times 6^\circ$ grid. The results are shown in Table 1b. We can summarize the situation as follows.

In Clusters A and B the measured mean flow at 1500 m is to the northwest and is quite stable spatially from mooring to mooring (Fig. 2). An exception is the southernmost mooring, 627, of Cluster B, where a mean direction is somewhat north of east. At the time of deployment of Cluster B, this mooring was south of the sharply defined edge of the Mediterranean salt water mass (Joyce, 1977). This water disappeared between the CTD at the southernmost mooring and those in the rest of Cluster B. After Clusters A and B were recovered, two site moorings were maintained at the locations of mooring 630 and mooring 623, respectively, in the two clusters for another year to explore the representativeness of the cluster data. Displayed in Figure 5 are 16-month average current vectors at the site moorings. All mean vectors are tabulated in Table 1a. From the 28-month long record at the center mooring in Cluster A (mooring 630 and its continuation, 648), we see that there is temporal stability only in the meridional component (Fig. 5). Because of the red
Table 1a. Locations and mean values of velocity and temperature at Array III moorings, including the two Cluster A and B site moorings.

<table>
<thead>
<tr>
<th>Cluster A</th>
<th>Site Mooring</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lat. (N)</td>
<td>Long. (W)</td>
</tr>
<tr>
<td>Instr.</td>
<td>(degrees)</td>
</tr>
<tr>
<td>6283</td>
<td>27.43°</td>
</tr>
<tr>
<td>6291</td>
<td>28.01°</td>
</tr>
<tr>
<td>6293</td>
<td>1500</td>
</tr>
<tr>
<td>6295</td>
<td>4006</td>
</tr>
<tr>
<td>6301</td>
<td>27.86°</td>
</tr>
<tr>
<td>6304</td>
<td>48.66°</td>
</tr>
<tr>
<td>6311</td>
<td>27.93°</td>
</tr>
<tr>
<td>6315</td>
<td>48.86°</td>
</tr>
<tr>
<td>6321</td>
<td>28.86°</td>
</tr>
<tr>
<td>6323</td>
<td>1488</td>
</tr>
<tr>
<td>6325</td>
<td>3993</td>
</tr>
<tr>
<td>Cluster B</td>
<td></td>
</tr>
<tr>
<td>6231</td>
<td>27.41°</td>
</tr>
<tr>
<td>6234</td>
<td>41.13°</td>
</tr>
<tr>
<td>6237</td>
<td>3927</td>
</tr>
<tr>
<td>6242</td>
<td>27.29°</td>
</tr>
<tr>
<td>6243</td>
<td>4076°</td>
</tr>
<tr>
<td>6245</td>
<td>40.35°</td>
</tr>
<tr>
<td>6251</td>
<td>27.24°</td>
</tr>
<tr>
<td>Cluster C</td>
<td>16.67°</td>
</tr>
<tr>
<td>-----------</td>
<td>--------</td>
</tr>
<tr>
<td>0791</td>
<td>142</td>
</tr>
<tr>
<td>0793</td>
<td>322</td>
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<tr>
<td>0794</td>
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<tr>
<td>0803</td>
<td>319</td>
</tr>
<tr>
<td>0804</td>
<td>520</td>
</tr>
<tr>
<td>0807</td>
<td>2520</td>
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<tr>
<td>0808</td>
<td>4020</td>
</tr>
<tr>
<td>0811</td>
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<td>538</td>
</tr>
<tr>
<td>0827</td>
<td>4038</td>
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</table>
Table 1b. Directly measured and geostrophically computed velocity differences.

<table>
<thead>
<tr>
<th>Cluster</th>
<th>Depths</th>
<th>Measured (cm/sec)</th>
<th>Geostrophically derived (cm/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>( \Delta u ) (east)</td>
<td>( \Delta v ) (north)</td>
</tr>
<tr>
<td>A</td>
<td>200-1500</td>
<td>-0.3</td>
<td>-1.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>+0.7*</td>
<td>-4.7*</td>
</tr>
<tr>
<td>B</td>
<td>200-1500</td>
<td>-1.3</td>
<td>-1.4</td>
</tr>
<tr>
<td>C</td>
<td>180-500</td>
<td>-4.8</td>
<td>-0.8</td>
</tr>
</tbody>
</table>


nature of the spectrum, the 200 m (or 500 m currents) are not well determined with even a 28-month long record at either A or B.

Figure 2 displays the mean current vectors at 4000 m, 500 m (1500 m in A, B) and 180-200 m levels. Note how well the 4000 m mean currents at all three clusters (and site moorings) follow local bathymetry. In the A and B areas the mean bottom circulation must be very complex; and in C there is a consistent, deep, northward flow into the western North Atlantic basin.

We can compare the means of the first year with those of the second year (Figs. 2 and 5). In Cluster A, the 200 m level current shifts from an east-northeast to a southeastward direction, and doubles in strength. At 1500 m, there is, as noted, little change between the years in the northward component. The eastward component changes sign. The 4000 m level is available only in the second year. At Cluster B the current at 200 m changes from a northwestward flow to a southeastward one. At 4000 m there is much less change in direction from one year to the next. We suspect this flow is following the very local bottom contours.

In Clusters A and B there is a well-defined counterclockwise rotation of the geostrophically derived mean flow from 1500 m to 200 m through the main thermocline; in Cluster C, the geostrophically derived mean flow between 500 m and 200 m is nearly in the same direction, but a strong counterclockwise rotation occurs between 200 m and the surface (e.g., Keffer and Niiler, 1982). As described by Bryden (1976) this pattern of vertical rotation of mean geostrophic current implies a negative horizontal mean advection of density. The three dimensional flow and the implications of the computed net heat and salt flux convergence in various theories of the reference level and mixing in Clusters A and B area are discussed by Keffer and Niiler (1982). In particular, the ‘beta-spiral’ technique of Behringer and Stommel (1980) for determining the reference level in Cluster B is consistent with the second year of observation at 200 m; but their results also imply an eastward flow at 1500 m which differs significantly from the observed flow except in the one year average of the southernmost mooring, 627 of Cluster B.
4. Temporal and spatial variability

a. Temperature records. Daily temperature records at those stations which have the most complete data (including site moorings) in each cluster are displayed in Figure 6 with energy in the superinertial frequency band removed by a low-pass filter. Fluctuations with time scales ranging from tens to hundreds of days are general features. Visual similarity between some time series is also evident. Detailed characteristics of these fluctuations vary with depth and location. The statistical relationships are discussed in Sections 4c and 4d.

No obvious annual signals can be seen in the Clusters A and B areas. However, a signal conceivably of annual period can be seen in Cluster C at depths above
Figure 6. Temperature as a function of time at moorings (a) 630, (b) 623, and (c) 81. The raw records were low-pass filtered with a half-power cutoff of two days for moorings 630 and 623 and four days for mooring 81, then subsampled daily.
663 m and is characterized by an abrupt increase in temperature around day 170 and gradual decrease until day 450 when the temperature begins to rise again. Observations of annual oscillations of the depth of the thermocline in the Pacific North Equatorial Current were reported and explained in terms of the baroclinic response to trade winds by Meyers (1979). Whether the apparent seasonal changes observed in Cluster C are of the same origin cannot be determined with a one-year record.
In the topmost records, the temperature variations with a shorter than seasonal time scale do not appear to be similar to thermoclinic-level ones except in the second half of the data from mooring 81 of Cluster C, where fluctuations at depths from 160 m to 663 m show a great deal of similarity. Most of the abrupt temperature changes in the upper levels here appear to be associated with the sign changes of the north-south component of the current vector (Fig. 7), advecting the north-south temperature gradient in the upper ocean.

The longest period variations of deep records of mooring 630-648 of Cluster A appear to occur consistently at all depths from 542 m to 4909 m. For example, the temperature maximum around day 360 appears in all records below 1498 m. The short-period (<50 days) fluctuations at 542 m are not so intense at the same depth in other clusters. In both Clusters A and B, the records in the main thermocline (496 m to 872 m) show many similar 15-20 day time scale features. In Cluster B, the records displayed (as well as those not displayed) show little similarity to each other in deeper water. In general, at 1500 m and above, the Cluster B temperatures show higher frequency "noise" than do those of A with the effect being most pronounced at the 1500 m level. This difference is presumably the result of the generally much greater diffuseness of the T-S relationship in B than in A (i.e., compare Figs. 3a and 3b).

As noted above, the temperature fluctuations at mooring 81 of Cluster C show a great deal of similarity between 160 m to 663 m. Notable features here are the
CLUSTER B MOORING 623-649

YEAR DAY 1977-1979

CLUSTER C - MOORING 81

JULIAN DAYS
occasional rapid excursions, or spikes, which are confined to these depths. Phenomena similar to these were also observed in the MODE area (Richman et al., 1977). The raggedness of the record at 663 m (and every other Cluster C record at this depth) is caused by the variability of the T-S relationship which results from the presence of the South Atlantic intermediate water (Fig. 3c). The records at 2509 m and 4008 m appear to have a predominant periodicity of about 70 days because about five temperature maxima appear in both. These seemingly regular deep temperature signals were not found in the MODE area.

b. Velocity records. Figure 7 displays the stick diagrams of the low-passed records of horizontal current velocity at the same moorings displayed in Figure 6. For moorings in Clusters A and B, velocity fluctuations at nominal depths 200 m and 1500 m are characterized by eddy-like features with time scales of about 50 days; these features tend to appear concurrently in both time series. Superimposed on these "eddies" are short-period fluctuations with time scales of about 10 days and with smaller amplitudes; usually these changes do not appear reproduced at both depths at the same time. At 4000 m, these records are dominated by short-period fluctuations in both clusters with a time scale of about 15 days in Cluster B and 25 days
in Cluster A. This difference in time scale may be related to the fact that the 4000 m record is closer to the bottom in Cluster B than it is in Cluster A, although it may also represent the difference between a deep "western" boundary and an "eastern" one. The long-period zonal fluctuations above 500 m are now believed to be common to the regions of POLYMODE Arrays I, II, and III.

c. Frequency spectra. To quantify the preceding discussion, we present two spectra (from Clusters B and C) of the horizontal kinetic energy, normalized by local buoyancy frequency, and area-preserving spectra of low-passed velocity and temperature data computed for the first year for records from all three clusters. The former is a test of the validity of the WKBJ approximation for the vertical structure (implying the dominance of high wavenumber structure) as a function of frequency; the latter is a convenient way to delineate the frequency structure of the energy-containing band of the spectra; however, see the warning note in Wunsch (1981) concerning the potentially misleading character of these displays.

Normalized kinetic energy spectra. Previous observations have shown that horizontal kinetic energy measured in the ocean interior scales in the vertical with buoyancy frequency (the so-called WKBJ scaling) in two frequency bands: (1) internal wave band (Garrett and Munk, 1975); (2) subinertial frequencies greater than about 1 cycle/30 days (the isotropic band, c.f. Richman et al., 1977; Wunsch, 1981). Figures 8a and 8b display two WKBJ scale spectra of horizontal kinetic energy. Those shown in Figure 8a are typical of all the moorings in both Clusters A and B.
In the band of 1 cycle/3 days to 1 cycle/30 days, in A and B, energy near the surface and bottom is significantly higher than at intermediate depths and may be related to surface forcing and bottom trapped waves (see Koblinsky and Niiler (1982) for a discussion of wind forcing). This result too is in contrast to many other regions. In the lowest band (1 cycle/66 days to 1 cycle/340 days), near-surface energy is greater than that at lower levels.

Fu (1980) discusses the behavior of the internal wave band in Clusters A and B. Judging from Figure 8b, the WKBJ scaling is valid in the internal wave band in
Cluster C but something more complex occurs in the other two clusters. At subinertial frequencies WKBJ scaling generally produces a universal spectral level, except possibly at the 500 m level of mooring 81 (as shown) and the 4000 m level of mooring 79 (not shown), where excessive energy is found. For comparison, a slope corresponding to $\omega^{-8}$ is drawn on Figure 8, but the spectral slope of the entire group is indistinguishable from $-2.5$, as reported by Richman et al. (1977) in the MODE area.

Low-passed velocity and temperature spectra. For selected moorings from each cluster, the area-preserving plots of the spectra of low-passed velocity and temperature at three depths are displayed in Figures 9a and 9b, respectively. Each spectral estimate has ten degrees of freedom except the two lowest frequency estimates, which have only two degrees of freedom.
At depths about 1500 m in Clusters A and B and above 2500 m in Cluster C, there is a well-defined “eddy-containing” band at about 1 cycle/100 days for $v$ velocity. In this range, energy is predominantly in the $v$ component except for mooring 623, where energy is more or less evenly distributed in $u$ and $v$ components. Energy in this band corresponds to those dominant energetic fluctuations seen in the stick diagrams (Fig. 7). There is significant amounts of energy at frequencies lower than 1 cycle/100 days in $u$ velocity. This low frequency zonal dominance is more pronounced in Clusters B and C than in A. Note that similar low-frequency fluctuations in $u$ were also observed in the thermocline in the MODE area (Richman et al., 1977).

At 4000 m, the spectra at Cluster C are similar to those at upper levels, whereas the spectra at Clusters A and B are different; the eddy-containing band is less well defined here. The presence of appreciable energy at about 1 cycle/10 days at 4000 m Cluster B reflects those energetic short-period fluctuations as seen in Figure 7b. The low-frequency current variance ellipse for the 1500 m level in A and B and the 500 m in C are displayed in Figure 13, in which entire subinertial frequency band polarization is displayed.

At Clusters A and C, there is also an eddy-containing band in the temperature spectra at all depths in a band centered at 1 cycle/100 days, corresponding to the one seen in the velocity spectra. At Cluster B, the temperature variance is dominated by energy at frequencies shorter than 1 cycle/100 days. It is interesting to note that there is an indication of low-frequency temperature variations at 160 m and 510 m at Cluster C. Recall that there are also low-frequency variations in $u$ in the thermocline at both Clusters B and C.

d. Time and space scales. The integral time scale of each long daily average record of $u', v', T'$ (primes denote the deviation from the record average) was computed from the integral of the square of the lagged auto-correlation function (Richman et al., 1977). Table 2 displays the cluster average values of these quantities as well as the results from MODE Center. A parenthetic value indicates that values at individual moorings vary by a factor of two. The temperature time scale is more consistent among the moorings in all clusters than the velocity time scale. It is vertically uniform in both A and C, with the exception of the small value at about 750 m at C which was noted from the visual inspection of the temperature records and is probably due to the erratic advection of South Atlantic Intermediate Water elements. The vertical structure of the temperature time scales is more complex at B, and as we shall see later, so are the vertically coherent structures of temperature variability. (The mid-water minimum time scale, for example, is in the Mediterranean water mass.) At 500 m, the 33 day time scale at C is half of the 62 day scale at B.

Velocity time scales in general are shorter than the temperature scales. As is found in temperature time scales, the velocity time scales in B are variable with depth and in A they are uniform with depth. At the upper two levels, velocity time scales are
Table 2. Time scales of variability at the three clusters compared to that at MODE Center. Values were computed from integral of square of correlation function. Parenthetical values indicate that individual records differed by a factor of 2 or more from each other.

<table>
<thead>
<tr>
<th>Depth range m</th>
<th>POLYMODE-III A (28N, 48W)</th>
<th>POLYMODE-II IB (27N, 41W)</th>
<th>POLYMODE-IIIC (16N, 54W)</th>
<th>MODE Center (28N, 70W)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>u  v  T</td>
<td>u  v  T</td>
<td>u  v  T</td>
<td>u  v  T</td>
</tr>
<tr>
<td>120-215</td>
<td>26  30 42</td>
<td>(62) (44) 26</td>
<td>(34) 21 30</td>
<td></td>
</tr>
<tr>
<td>230-260</td>
<td></td>
<td></td>
<td>43</td>
<td></td>
</tr>
<tr>
<td>320-340</td>
<td></td>
<td>(45) 20 41</td>
<td></td>
<td></td>
</tr>
<tr>
<td>480-540</td>
<td>(41) (62)</td>
<td>(51) 19 33</td>
<td>70 23 36</td>
<td></td>
</tr>
<tr>
<td>660-850</td>
<td></td>
<td></td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>1420-1530</td>
<td>32  35 50</td>
<td>(52) 68 23</td>
<td>39</td>
<td>20 28 32</td>
</tr>
<tr>
<td>2440-2830</td>
<td>(26) (23) (47)</td>
<td>(20) (14) 37*</td>
<td>(34) 29 (33)</td>
<td>21 26 23</td>
</tr>
<tr>
<td>3400-4040</td>
<td>* two record average.</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

larger in B than in A. In Cluster C, the \( u' \) time scale is nearly twice as large as the \( v' \) time scale and is variable among the moorings in the cluster. To the extent that the data allow a conclusion to be drawn (there are problems of comparing different depths), it appears that the time scale becomes larger eastward along 28N from the MODE Center to Clusters A and B. This was observed by Richman et al. (1977) to be a tendency in the POLYMODE Array I moorings. In contrast, in Cluster C at the 500 m level, the time scale is smaller than in MODE Center.

The correlation coefficient as a function of horizontal spatial separation for the daily average records at Clusters A and B is graphed in Figure 10. With the large degree of scatter in the comparatively small quantity of data we do have, the most confident assertion is that at 1500 m and above in Clusters A and B, both components of velocity become uncorrelated at about 100 km. At the nominal 4000 m level, the correlation distance is evidently much smaller, of the order of 50 km, presumably because of topographic effects. In Cluster C, the spatial scale of \( v' \) component velocity at 500 m (not shown) is comparable to those in A and B at 1500 m, whereas the spatial scale of \( u' \) component velocity at these levels is larger. At 4000 m, both components of velocity seem to have larger spatial scales than those in A and B. All these estimates are based on the premise that the variations are isotropic. However, note in Figure 10a and 10b the \( u' \) spatial scale at 4000 m, Cluster C, is 100 km, and it is smaller than the \( v' \) spatial scale which is not resolved by this array (see Fig. 2c for the array configuration).

Temperature spatial correlations can be compared to those computed for the MODE-1 area by Richman et al. (1977); at 500 m, all three of the present clusters seem to show a spatial scale which is somewhat larger than in MODE. At 1500 m,
Clusters A and C show a spatial scale considerably larger (the MODE correlation crossed zero at about 60 km). Only Cluster B at 1500 m has a scale as short as in the MODE area (remember this is the depth of maximum influence of the Mediterranean water on the temperature fluctuations). At 4000 m, the spatial scale of the temperature fluctuations is definitely larger than in the MODE area, even over rough topography.

Because the most energetic fluctuations of each variation \( u' \), \( v' \), and \( T' \) are generally spatially correlated within each cluster (except at the nominal depth of 4000 m in Clusters A and B), horizontal phase propagation, or relationships between space and time scales, can be investigated by computing the horizontal correlation coefficients as a function of separation vector at different time lags. (Figs. 10a,b are the
correlation coefficients as a function of separation distance at zero lag.) We computed the lagged correlation coefficients as a function of vector separation for $v'$ at all clusters. At the 1500 m in Cluster B there is a clear southwestward phase propagation of about 3 km/day and at Cluster A, a similar westward component occurs, with a less clearly defined north-south component. At 500 m depth in Cluster C, the meridional scale is longer than the zonal scale. Westward phase propagation of about 3-5 km/day was seen for small time lags. At all clusters, similar propagation was found in the $T'$ field, but no significant structure was found in the $u'$ field.

In interpreting the phase propagation observed in Cluster C, recall that the mean flow at 500 m is also westward with a spread of 1-2 km/day. The apparent phase propagation may be partly due to the advection of a stationary perturbation by the mean flow but cannot be explained entirely by it. In Clusters A and B the mean flow at 1500 m is also about 1 km/day to the northwest (except for mooring 627, Cluster B) and the observed phase propagation may be an intrinsic property of the eddy field. Southwestward propagation with speed about 4 km/day was observed in the MODE area (The MODE Group, 1978).

e. Empirical orthogonal functions. The important vertically coherent variations are most simply viewed in terms of the empirical orthogonal functions (EOFS) of the vertical covariance matrix (Lumley, 1970). These are graphed in Figures 11 and 12 for the vertical displacement, $\zeta'$ and horizontal velocity, $v'$ respectively. The velocity functions are drawn so that the maximum vector is unity and the bottom vector is along the positive $x$-axis. Cluster A, mooring 630, presents the simplest picture. Most of the variance is associated with the vertical displacement of the main thermocline, very much like a dynamical mode, and the second most energetic fluctuation is surface trapped. One velocity mode, which is quite baroclinic, accounts for 96% of the overall variance, but does not account for the variance at 4000 m because 1500 m and 4000 m currents are not correlated while those at the 200 m and 1500 m levels are. Of course this 3-point mode does not resolve the vertical structure well. The 200 m and 1500 m currents account for most of the energy in the column. This cluster is much like the MODE-1 area which has often been summarized by saying that the motion is dominated by a single baroclinic mode, i.e., a bulk vertical displacement of the thermocline.

In Cluster B, both at moorings 623 and 625, a single velocity mode accounts for 96% of the variance field of velocity. It looks identical to that at Cluster A. However, to represent 98% of the variance in the vertical displacement structure requires three modes. The most energetic mode is bottom trapped and accounts for 61% of the variance. The second most energetic mode accounts for 24% of the variance, and resembles the most energetic mode in Cluster A. We also computed the displacement EOFS at the southernmost mooring, 627, Cluster B; here two modes account for 64% and 30% of variance, respectively, with significantly different shapes than
in mooring 623. Thus despite their close proximity, temperature variability at Clusters A and B is quite different.

Cluster C has the most complex vertical structure. At mooring 81 (and also at 79) three modes are required to represent 86% of the displacement variance (at mooring 81, 47%, 23%, 16% of the variance by modes 1, 2, 3, respectively; and at mooring 79, 65%, 21%, 9.2% of the variance by modes 1, 2, 3, respectively); although the dominant mode again closely resembles a bulk vertical displacement of the thermocline. Two modes are required to represent 95% of the velocity variance at both moorings 81 and 82. The most energetic velocity modes are similar at all
clusters with velocities at all depths approximately in the same direction.

In summary, the apparent vertical coherence of energy-containing variations through the water column in Cluster A is similar to that found in the MODE area, whereas the variations in the vertical observed in Clusters B and C contain more complex features.

5. Comparison with other regions

A major purpose of the setting of Array III was to produce an overall comparison of variability in the North Atlantic. Schmitz and Holland (1982) have already used some of this data as a qualitative test of the ability of an eddy-resolving general circulation model to reproduce the gross features of the basin-wide changes in eddy characteristics.

Here we will attempt to describe further these gross variations by making some comparisons between Array III and the results of MODE-I and Arrays I and II of POLYMODE. We will be fairly brief for two reasons. A preliminary intercompa-
son is given by Wunsch (1981) and, a considerable number of additional observa-
tions have been obtained in the North Atlantic outside of the immediate POLY-
MODE organization. We anticipate that more comprehensive syntheses of the North
Atlantic mesoscale variability will be attempted in the immediate future.

A fundamental difficulty lies in selecting properties of the field which are both
measurable and of physical significance. In trying to define the descriptive oceanog-
raphy of eddies we will discuss energy levels, spectral shape and coherence scales in
somewhat gross terms. From the characteristics of the three clusters already de-
scribed, the reader can recognize that there exists a very large amount of detailed
structure as a function of position in each cluster that is difficult to describe and
whose significance either statistically or physically is not obvious.

a. Kinetic and potential energy distribution. Table 3 shows the cluster averages of
the eddy kinetic energy and the eddy potential energy. Both quantities are computed
from the daily fluctuation records of $u'$, $v'$, $T'$ of eastward and northward fluctuation
velocity and temperature, respectively, using the formulas $K.E.' = \frac{1}{2}(u'^2 + v'^2)$ and
$P.E.' = \frac{1}{2}N^2T'^2/(dT/dz)^2$. Here $N$ is the buoyancy frequency and $(dT/dz)$ is the
temperature gradient computed from the CTD casts at each mooring. For compari-
son, similar quantities for the MODE area and POLYMODE Arrays I and II are
also presented. Array I falls roughly on the same latitude circle as Clusters A and B
(Fig. 1). In Table 3, a cluster average quantity is computed at levels where two or
more complete records of a variable are available (335 days in A and B and 353
days in C). Because there are at most four complete records of any quantity at any
specific level, an estimate of the significance of the cluster mean was not attempted.
Specific note is made of exceptional levels of $K.E.'$ or $P.E.'$. The second year data
from site moorings are included in parenthesis. Note the Array II values are based
upon 27 months of data.

The kinetic and potential eddy energy at 500 m along the 28N latitude band first
decreases eastward from MODE Center to 55W then increases to Cluster A; the
potential energy continues to increase across the ridge to Cluster B. Cluster C, $K.E.'$
and $P.E.'$ at 500 m are of intermediate magnitude compared to the 28N values. At
1500 m, $K.E.'$ at Clusters A and B is less than at MODE Center and is comparable
to MODE East; however, the $P.E.'$ at A and B is three times larger than the value
at MODE East. The Array II values reflect the very large kinetic energies at all
depths as we approach the Gulf Stream system (Schmitz, 1978).

The small temperature variance at 1500 m in Cluster A is due to the smoother
low-frequency signal in the records and, because the water mass variability is not
apparent in the CTD traces there, we interpret our computed $P.E.'$ as a good mea-
sure of the actual eddy potential energy. However, at Cluster B, all five 1500 m
records show a ragged, high frequency temperature variability. We are not sure how
much of this temperature variance is due to vertical motions and hence potential
Table 3. Eddy kinetic and potential energy from Array III and from a few other locations.

<table>
<thead>
<tr>
<th>Depth range (m)</th>
<th>POLYMODE-III A (28N, 48W)</th>
<th>POLYMODE-III B (28N, 48W)</th>
<th>POLYMODE-III C (28N, 55W)</th>
<th>POLYMODE-I (28N, 55W)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>K.E.'(cm^2 sec^-2) P.E.'</td>
<td>K.E.'(cm^2 sec^-2) P.E.'</td>
<td>K.E.'(cm^2 sec^-2) P.E.'</td>
<td>K.E.'(cm^2 sec^-2) P.E.'</td>
</tr>
<tr>
<td>120-215</td>
<td>54.9 (74.0)</td>
<td>73.2 21.8</td>
<td>31.7 72.6</td>
<td>9.0 10.0</td>
</tr>
<tr>
<td>230-260</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>320-340</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>480-540</td>
<td>35.7</td>
<td>35.9* 55.6</td>
<td>26.5 39.4</td>
<td>9.0 10.0</td>
</tr>
<tr>
<td>600-850</td>
<td>1.8 23.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1420-1530</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2440-2830</td>
<td>1.0 4.8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3400-4040</td>
<td></td>
<td></td>
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</tbody>
</table>

* with #79
*#623 only
*#624 only

<table>
<thead>
<tr>
<th>Depth range (m)</th>
<th>MODE Center (28N, 67.7W)</th>
<th>MODE East (28N, 68.7W)</th>
<th>Array II (36N, 53.8W)</th>
<th>Array III (31.5N, 55W)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>K.E.'(cm^2 sec^-2) P.E.'</td>
<td>K.E.'(cm^2 sec^-2) P.E.'</td>
<td>K.E.'(cm^2 sec^-2) P.E.'</td>
<td>K.E.'(cm^2 sec^-2) P.E.'</td>
</tr>
<tr>
<td>480-540</td>
<td>39.5 32.0</td>
<td>33.0 22.5</td>
<td>269.0 49.4</td>
<td>49.4</td>
</tr>
<tr>
<td>600-850</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1420-1530</td>
<td>7.4 3.1</td>
<td>61.0 10.8</td>
<td>10.8</td>
<td></td>
</tr>
<tr>
<td>3400-4040</td>
<td>8.6 11.0</td>
<td>7.4 5.2</td>
<td>84.2 9.8</td>
<td>9.8</td>
</tr>
</tbody>
</table>
K.E.’ and P.E.’ seem to be controlled both by bottom roughness and the upper level variability. MODE East and Cluster C are in slightly rough bottom areas and the bottom energy levels are comparable. Clusters A and B exhibit a more drastic vertical decay of K.E.’ to the rough bottom than occurs at MODE East or Cluster C. Evidence for increase of P.E.’ near the bottom is seen at Cluster A and most dramatically, of both K.E.’ and P.E.’ at mooring 79, Cluster C.

In Array III we obtained, for the first time in POLYMODE, long records at the top of the main thermocline between 120-215 m. In each cluster three long current records exist and there is at most a 10% variation in K.E.’ among the separate moorings in each cluster. At all three clusters K.E.’ decreases with increasing depth through the main thermocline although this is less dramatic at C. At each upper level instrument in Cluster A and C, $\nu'^2 > u'^2$ and in Cluster B $u'^2 > \nu'^2$. Except for the 300-500 m level at 81 in Cluster C, we find $\nu'^2 > u'^2$ (viz., Fig. 13).

In Clusters A and C the spatial inhomogeneity of P.E.’, within the cluster is larger than at B. Clusters A and C show a maximum value of P.E.’ at the surface. At all moorings in C, P.E.’ decreases with increasing depth and then increases again to a local maximum between 320-540 m, but the exact vertical distribution is somewhat different at each mooring. Keffer (1982) computed the fluctuation potential energy distribution as a function of depth from the historical hydrographic data (viz., Fig. 4) in the Cluster C area. This data show a minimum at 250 m depth similar to that found in the moored temperature data in Table 3. In A, there appears to be a uniform vertical decrease of P.E.’. However, because of vertical sampling, we do not know whether a relative maximum occurs between 500 m and 200 m, as there is in Cluster C. In Cluster B, the near-surface value of P.E.’ is less than that at the 500 m level. At Clusters A and C the thermal field variance in the upper portion of the main thermocline is horizontally more inhomogeneous than at Cluster B, while the thermal field variance at Cluster B is horizontally more inhomogeneous below the main thermocline than it is at Clusters A and C.

In summary, in Array III the mid-water K.E.’ and P.E.’ are comparable to central MODE region values. There is a relative increase of K.E.’ from the 500 m to 200 m level, and, over rough topography, a sharp decrease of both K.E.’ and P.E.’ to the ocean bottom. The horizontal inhomogeneity of the P.E.’ distribution in and above the main thermocline is observed where there is a north-south polarization of the low-frequency currents; in some moorings there is bottom trapping of P.E.’ and K.E.’. As noted earlier by Schmitz (1976, 1978), Richman et al. (1977), and Wunsch (1981), the gross energy variations of the mid- and upper-ocean remain consistent with a general intensification toward the Gulf Stream system with secondary maxima toward other boundaries. Consistent with Dantzler’s (1977) potential energy diagram, there seems to be a broad minimum of kinetic and potential energy in the thermocline centered near 28N stretching at least from the Hatteras abyssal plain to Cluster B (and all the way to Africa according to Dantzler). However, there is no
justification for calling this region an “eddy desert” as there is only a quantitative, not a qualitative change in energy levels over the North Atlantic.

Generally speaking the differences between kinetic energy spectra in the North Atlantic are subtle. All seem to be red, with a $-3$ or $-2.5$ slope form from periods of a day or so through an eddy-containing band at 50-100 days, with a decline in energy, or at least a leveling off in the rate of rise, at longer periods. As Schmitz (1978) notes, there tends to be a shift of the eddy energy peak toward higher frequencies (a “blue-shift”) in the more energetic regions near the Gulf Stream recirculation. Here a similar effect is produced by a “stretching-out” of the dominant time scales eastward along 28N.

The most striking difference between the MODE area and the Mid-Atlantic Ridge is the loss of energy in deep water over rough topography. As noted by Schmitz and Holland (1982) this is a feature that two-layer numerical models have not yet been able to reproduce. Our observations suggest that at least a three-layer model is required also for resolving the more complex vertical structures at Clusters B and C.

The potential energy over the entire region is much less variable than is the kinetic energy. Richman et al. (1977) note this reduced variability is consistent with Schmitz'
(1978) findings in the high kinetic energy regions where the motions have a much greater tendency to be barotropic.
b. Length scales. Apart from the topographically controlled motions at 4000 m, the horizontal length scales of the motion are somewhat greater than in the MODE area. In Clusters A and B at least, this may be just a reflection of the stretching out of the time scales. The vertical scale of motion in Cluster A is similar to MODE, primarily a single vertical mode carrying some elements of both the barotropic and first baroclinic linear modes. Clusters B and C are more complex in the vertical, with B showing signs of bottom intensification.

6. Baroclinic instability

If the eddy field is locally converting mean potential energy of the main thermocline to eddy energy, the horizontal eddy density flux (or eddy temperature flux, $v'T'$) has a component opposite to the direction of the mean horizontal density gradient (or mean temperature gradient $T$), i.e., down gradient (see Gill et al., 1974). We computed the eddy temperature transports at all instruments with long records. Possibly significant fluxes (correlation coefficient between $v'$ and $T'$ greater than 0.3 but with unknown degrees of freedom) that are consistent within a cluster, occur between 160 m and 500 m in Cluster C and at the 1500 m level on the three westernmost moorings in Cluster B (623, 626, 627). We also computed the cospectra between the time series of $v'$ and $T'$ and find when consistent fluxes (or correlation coefficients) occur, the contribution to these comes from 60-20 day period components of the time series. Recall that between 150 m and 500 m at Cluster C there is a well-defined water mass, and at 1500 m, in Cluster B, the water mass variability appears at relatively much higher frequency than the frequency band where we obtain the significant covariance contributions.

In Figure 13 the heat flux vectors and the velocity variance ellipses at 500 m in Cluster C and 1500 m in Clusters A and B are plotted. There is a second year of record at 1500 m in Cluster A, mooring 630; here the temperature flux vector changes from a southwestward to a southeastward direction (dashed on Fig. 13a). Recall that there is a very low frequency zonal oscillation in this area, and the heat flux vector, while having a stable meridional component over two years, has an indeterminate zonal component. The estimate of the direction of the historical density gradient at 500 m in Cluster C (Fig. 13c) and the vertically averaged horizontal density gradient of Clusters A and B between 1000 and 2000 m are shown. Also shown are the first year temperature gradient vectors determined from the mean temperature of the moored data at 200 m and 300 m at Cluster C (Fig. 4). While the magnitude of the directly measured temperature gradient vector is somewhat larger than the historical one, both point in the same direction. In the upper layers of Cluster C the cluster averaged eddy heat flux, although marginally significant at the 90% level, is to the northeast, and the historical density gradient is at precisely
right angles to this flux. At moorings 80 and 82 there is a conversion of potential energy, but at moorings 81 and 79, the conversion is in the opposite sense and of the same magnitude. The very low frequency, or "secular scale," variation in the east-west direction at mooring 81 is more intense than at the other moorings and this results in an east-west oriented variance ellipse.

To the extent that we can determine, in Cluster B the temperature flux vector is directed to the southeast, in the opposite direction of the density gradient, indicating if anything, a decaying eddy field. The Cluster A picture seems to indicate a neutral or slightly decaying eddy field.

It is interesting to compute how rapidly eddies could convert potential energy to kinetic energy if conditions at each mooring in Cluster C were viewed individually. We do wish to point out that this property of the eddy field is not homogeneous within Cluster C elements. This calculation gives an upper bound on the process which may be very localized in the ocean. At mooring 82 there is a well-developed shear of mean currents through the thermocline to the southwest and an eddy temperature flux to the southeast (a significant correlation coefficient of 0.6 between v', T'). Here an estimate of the local rate of eddy conversion is \( \frac{\partial \rho}{\partial T} \frac{\partial v}{\partial z} \) in a geostrophically balanced mean current of shear \( \frac{\partial v}{\partial z} \) where \( v'T' \) is the component of the temperature perturbation flux projected to the left of the mean shear, \( \alpha = \frac{\partial \rho}{\partial T} \) taken from CTD casts near mooring 82, \( f \) is the Coriolis parameter, \( g \) is the gravitational acceleration and \( N \) is the buoyancy frequency. Between 300 m and 500 m at mooring 82 and using appropriate values of the parameters we find a conversion rate of about \( 1.3 \times 10^{-5} \) cm² sec⁻². The average of \( K.E.' + P.E.' \) at these levels is 76.4 cm sec⁻². A time scale for doubling the local eddy energy level therefore, is about 68 days. In Cluster C the vertical shear at mooring 82 is the most stable and varies on a time scale long compared to an eddy period. Therefore, eddies could be created at Cluster C locally where the ocean shear is favorable for their creation for a few months and theoretically eddies created in Cluster C would have a horizontal scale of less than 100 km. However, because of the general lack of statistical stability among other elements of the Cluster C, we must conclude there is no reliable evidence (from the eddy heat flux measurements) for significant large horizontal scale eddy generation in this region of the North Equatorial Current.

A second feature of linear baroclinic instability models is the prediction of upward phase propagation (Gill et al., 1974) for a zonal current as in Cluster C. This phase difference should occur mainly in the upper 500 m. Examination of a phase plot (not shown) and of the cross spectrum suggests there are appropriate phase differences at periods greater than 30 days in meridional velocity at moorings 81 and 82. But the temperature and zonal velocity results are too complex to be interpreted this way.
7. Final remarks

Array III was set largely for descriptive purposes, i.e., to define the geographical variability of mesoscale variability in the western North Atlantic. We have seen that Cluster A just west of the Mid-Atlantic Ridge has similar characteristics to the MODE area. The major changes are a tendency toward increased energy of the dominant motions in lower frequencies, the meridional dominance of the eddy field, and the suppression of the deep water energies over the very rough topography.

Cluster B just east of the Mid-Atlantic Ridge is surprisingly different from A. There is evidence of bottom trapping at Cluster B. Perhaps this is a manifestation of a tendency to form western boundary currents in the deep water, and a much more pronounced effect of the Mediterranean water. The occurrence of a gap in the T-S relationship here (Joyce, 1981) and the abrupt variability of the mean flow is part of a puzzle relating to the interaction of the water mass, the topography, and the eddy field that we have not begun to sort out. Time scales at Cluster B are generally larger than in Cluster A and the kinetic energies are slightly larger. There is also a tendency for more zonal dominance at the lowest resolved period.

Cluster C in the North Equatorial Current has a more complex variability in the vertical than we anticipated. As in the other two clusters, the kinetic energy was dominated by its meridional component in the eddy-containing band and by its zonal component at longer periods. The idea that this region should exhibit a comparatively simple form of baroclinic instability is not borne out.

The main body of this paper describes detailed differences between the clusters, between different moorings within clusters, and different depths on the same mooring. It is difficult to summarize this detail and we do not really know which features would survive averaging over longer data sets, or which features would prove to be of dynamical significance.

Generally speaking, the variation of the mesoscale eddy field we have seen thus far seems quite subtle, and requires all the details we have had to describe. Almost everywhere we see an isotropic high frequency portion to the spectrum, and eddy-containing band, and a tendency of the lowest resolvable frequency motions to zonality; although there are a great many detailed differences from location to location. As already noted, we do not see evidence that clearly confirms simple baroclinic instability mechanisms, although we see tantalizing hints in places; there is also a hint of some relationship to the wind field at least in Cluster C; however, beyond this, direct evidence for the origin of the open ocean mesoscale still eludes us. The Array III data clearly indicate the importance of finite amplitude topography for controlling the energy levels in deep water, but here existing theory is of little help. Finally, the role of eddies in carrying heat in the ocean, insofar as Array III is representative, is weak and may not be significant in a global context.

Acknowledgments. This research was supported in part by the National Science Foundation through Grants OCE 78-19833 at MIT and OCE 76-2515 at Oregon State University, and by
the Office of Naval Research through Contract N00014-76-C-0197 at the Woods Hole Oceanographic Institution. We are grateful to the captains and crews of the research vessels *Knorr*, *Gillis* and *Gyre* for carrying out the work at sea and to the Moored Array Group at Woods Hole Oceanographic Institution, and to the Buoy Group at Nova University for deploying and recovering the moored arrays. The Draper Laboratory oceanography group prepared and read the temperature/pressure recorder data. The CTD group at WHOI and the GEOSECS operations groups at Scripps Institution of Oceanography obtained the hydrographic data. This is MODE Contribution number 161 (POLYMODE).

REFERENCES


Received: 22 January, 1981; revised: 4 February, 1982.