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Abyssal eddy kinetic energy in the North Atlantic

by William J. Schmitz, Jr.[1]

ABSTRACT

Both eddy and mean fields have similar zonal and meridional scales of geographical variation in the mid-latitude North Atlantic. The first map of the North Atlantic that contained estimates of the intensity of the abyssal eddy field is now several years old, and in the interim the relevant data base has increased roughly six-fold. Contemporary charts are presented, containing these more recent observations, along with some new styles of data presentation. The basic picture of maximum abyssal eddy kinetic energy near the fully developed Gulf Stream is consistently substantiated, along with a two order or magnitude latitudinal decay (from about 10^2 to roughly 1 $cm^2\ s^{-2}$) into the interior of the subtropical gyre west of the Mid-Atlantic Ridge. Results obtained in the last few years lead to the first relatively clear-cut identification of the zonal scales of variation of eddy intensity near the Gulf Stream. Eddy kinetic energy levels at abyssal depths near Cape Hatteras, in the vicinity of the Grand Banks, and east of the Mid-Atlantic Ridge are down by 1–2 orders of magnitude from maxima near the Gulf Stream at intermediate longitudes in the western North Atlantic. Preliminary contour maps of observed abyssal eddy kinetic energy are presented, albeit in schematic form.

1. Introduction

The currents in most regions of the world's oceans are highly variable in time and in space, with the largest amplitude fluctuations occurring in the vicinity of strong, persistent flow regimes (Schmitz *et al.*, 1983). The first map exhibiting abyssal eddy kinetic energies (Schmitz, 1976a, hereafter S76) contained values for the North Atlantic from roughly 1 to 100 $cm^2\ s^{-2}$, in contrast to a factor of only 2 to 3 variation for surface kinetic energy estimates (Wyrtki *et al.*, 1976; see, however, newer articles by Richardson, 1983a; and Douglas *et al.*, 1983). Latitudinal and zonal scales of variation for eddy kinetic energy at all depths are similar to corresponding scales of variation in the mean flow (Schmitz and Holland, 1982; Schmitz *et al.*, 1983). These are probably most sharply defined at abyssal levels since there is generally less observational uncertainty in estimates of eddy kinetic energy at depth, and because there are geographically two orders of magnitude of abyssal variation in contrast with one (nominal) at the surface or at thermocline depths. There is usually less observational uncertainty in estimates of abyssal relative to upper level eddy kinetic energies

1. Woods Hole Oceanographic Institution, Woods Hole, Massachusetts, 02543, U.S.A.

because there is less vertical shear, a more benevolent temporal spectrum, and less direct interference by the effect of wind and waves.

The present note is analogous to S76, but relies upon a considerably more substantial observational base and new styles of presentation. In particular, the first contour charts for abyssal eddy kinetic energy are introduced. The initial distribution of abyssal eddy kinetic energy published by S76 has also been updated to some extent by Schmitz (1977, 1978), Schmitz and Holland (1982), and Dickson (1983). The latitudinal scales of variation for abyssal eddy kinetic energy intially suggested by S76 have consistently been substantiated by all techniques of observation and analysis. The most basic feature is a maximum near the mean position of the upper-level Gulf Stream, similar but not precisely the same as the pattern observed (Cheney *et al.*, 1983; Dantzler, 1977; Douglas *et al.*, 1983; Emery, 1983; Richardson, 1983a, 1983b; Wyrtki *et al.*, 1976) at thermocline depths and higher. Upper-level eddy kinetic energies west of the Mid-Atlantic Ridge are intensified along a southeast-northeast direction and abyssal levels more south-north, much like the orientation of the means. This type of pattern is also evident in finer-scale limited-area eddy kinetic energy contour plots based on SOFAR float data (Rossby *et al.*, 1983). The largest zonal scales of variation of abyssal eddy energy near the Gulf Stream may now be identified clearly. This is made possible by the acquisition of key new data sets by Fofonoff and Hendry (1984), Gould (1983), and Johns and Watts (1984), (see also Casagrande, 1983; Dickson, 1983; Dickson *et al.*, 1982; and Gould and Cutler, 1980).

The geographical distribution of eddy kinetic energy and other characteristics of the horizontal Reynolds stress tensor are taken to be the basic descriptors of the eddy field, much as streamline or transport patterns for mean or quasi-permanent currents. The principal technique of exposition by S76, and here, consists of simultaneous plots of properties of both eddy and mean field: the essential point is that they are related both kinematically and dynamically (Schmitz and Holland, 1982; Schmitz *et al.*, 1983). In addition to a basic description or representation of the fluctuating field, distributions of eddy properties may be used as guideposts for model development (Schmitz and Holland, 1982; Holland *et al.*, 1983). The observation that the area of highest intensity for the eddy field is associated with the Gulf Stream System, which includes a recirculation west of the Mid-Atlantic Ridge, suggests that eddies are generated there, presumably due to instability processes (the possibility that these eddies affect the mean flow is also pertinent). The symmetry (shape) of the horizontal or geographical distribution of abyssal eddy kinetic energy implies that deep eddies are not likely to be predominantly a fluctuating response to time-dependent wind forcing (see Schmitz *et al.*, 1983), except in relatively low energy regions. There is no existing model of this type of forcing that leads to mean flow-related geographical inhomogeneity of the type observed for abyssal eddy kinetic energy, whereas there is some agreement in observed geographical distribution with the results of steady wind-forced "instability models" (Schmitz and Holland, 1982; Holland *et al.*, 1983; see also Hogg, 1984, for a direct discussion of the instability process for the type of data under consideration). However, the longitudinal response of the class of models examined by Schmitz and Holland (1982) is not yet well understood: the data needed to make a relatively definitive zonal scale intercomparison are new (not available to Schmitz and Holland, 1982) and analyzed and presented in the pertinent way for the first time below.

Observations of surface currents and temperatures, and of upper level temperatures in the depth range accessible to standard sampling by bathythermograph probes, have been made routinely over broad regions of the oceans. The coverage is adequate for construction of maps of time averages (means) and the intensity of the variability about these means on 1 to 5 degree grids covering large areas of the world's oceans, most notably in the northern hemisphere (Cheney *et al.*, 1983; Dantzler, 1977; Douglas *et al.*, 1983; Emery, 1983; Richardson, 1983a; Wyrtki *et al.*, 1976). Sampling density has been inadequate for construction of maps of eddy properties for the abyssal ocean.

A qualitative or semi-quantitative picture of the basic pattern of abyssal kinetic energy for the mid-latitude oceans has been developing over the past several years, primarily for the North Atlantic. This presentation will conclude with the initial contour chart for abyssal K_E in the North Atlantic subtropical gyre, in an essentially schematic form. Abyssal eddy kinetic energy values are also superimposed on charts of surface K_E and thermocline eddy potential energy. This first qualitative or semi-quantitative (order of magnitude) picture of the abyssal eddy field is more complete in particular latitude/longitude ranges: there are key data gaps remaining. Prominent examples for the subtropical gyre are in its interior, in the North Equatorial Current regime (notably to the east) and in the Gulf Stream System between 55 and 70W. One might expect the maximum abyssal K_E for the gyre to occur in the latter area. The Newfoundland Basin also needs more exploration, as do high latitudes in general. At present, the low energy and low latitude regions of the North Atlantic are undersampled. One vertical eddy kinetic energy section for the North Atlantic, along 55W, has recently been published (Richardson, 1983b). Characteristics of the eddy field are also discussed in review articles by Dickson (1983), Schmitz *et al.* (1983), and Wunsch (1981, 1983). Mid-latitude regions of the abyssal North Pacific, analogous to those described here for the North Atlantic, are presently being explored geographically (Schmitz *et al.*, 1982; Schmitz, 1984). Some geological implications of the kind of results presented herein have just been described by Hollister and McCave (1984).

2. Data sources and discussion

The first chart (S76, Fig. 1 there) of the North Atlantic containing values of abyssal eddy kinetic energy was based on long-term observations at seven sites. These estimates were superimposed on a map containing transport streamlines for the (mean or quasi-permanent or) general circulation at depths less than 4°C potential temperature as drawn by Worthington (1976). Similar results from roughly 45 locations are

Table 1. Estimates of abyssal (typically at 4000 m depth) eddy kinetic energy (K_E) at indicated locations in the North Atlantic. The observations are organized into three columns by longitude range: (i) 68–75W; (ii) 48–65W; (iii) 25–47W.

LAT. (°N)	LONG. (°W)	K_E ($cm^2 s^{-2}$)	LAT. (°N)	LONG. (°W)	K_E ($cm^2 s^{-2}$)	LAT. (°N)	LONG. (°W)	K_E ($cm^2 s^{-2}$)
37.7	69.7	74	41.5	55.0	91	38.4	46.8	71
37.0	70.0	104	39.5	55.0	127	40.1	44.6	40
36.7	70.0	113	38.5	55.0	138	38.8	44.9	25
35.8	70.5	65	36.0	55.0	107	39.1	42.3	30
32.7	70.8	50	35.3	55.0	80	37.0	42.0	6
31.0	69.5	30	31.5	55.0	10	27.2	40.9	1
31.5	68.5	25	28.0	55.0	1	52.7	34.0	21
28.0	70.0	9	15.2	53.8	4	52.2	31.0	10
25.5	70.7	16	40.2	62.6	77	41.0	23.3	2
36.0	73.2	15	34.0	60.0	18	33.0	22.0	3
36.0	74.6	10	33.0	64.4	25	42.0	17.0	1
36.0	73.8	31	33.0	57.5	18	46.0	17.0	1
36.0	73.0	47	31.0	59.9	1	42.0	14.0	5
31.1	73.4	63	28.0	65.0	1	47.0	10.0	2
31.0	76.7	20	27.7	48.7	1			
30.7	74.2	35						
23.5	72.5	60						

entered on the maps presented in the following. Here the label abyssal applies to depths well below the main thermocline, 4000 m being typical. Long-term refers to a minimum duration of roughly a year. For present purposes, all time series of velocity components (u and v denote eastward and northward, respectively) were initially low-pass filtered to remove contributions from frequencies higher than a cycle per 2 days (nominal). Time averages are denoted by an overbar, deviations from these averages by a prime. Eddy kinetic energy (symbol K_E) is defined to be .5 $(\overline{u'^2} + \overline{v'^2})$. Actual dimensions are of kinetic energy per unit mass; the latter will be hereafter understood. Available K_E estimates from the abyssal North Atlantic are listed in Table 1. Each column in this table contains data from one of three broad longitude ranges, as described in the following.

As the point of departure, the data from Schmitz (1976a) are presented in Figure 1, where only a few transport streamlines have been selected from Worthington's (1976; Fig. 11, p. 28) deepest "permanent" circulation diagram for clarity in presentation. The reader is referred to Worthington (1976) for a description of this flow model and its preparation. The use of portions of Worthington's (1976) abyssal or deep circulation diagram does not imply that this scheme for the North Atlantic circulation is assumed to be without fault. Rather, it is the existing account that offers a way to display the gross properties of the relation between the distribution of the intensity of

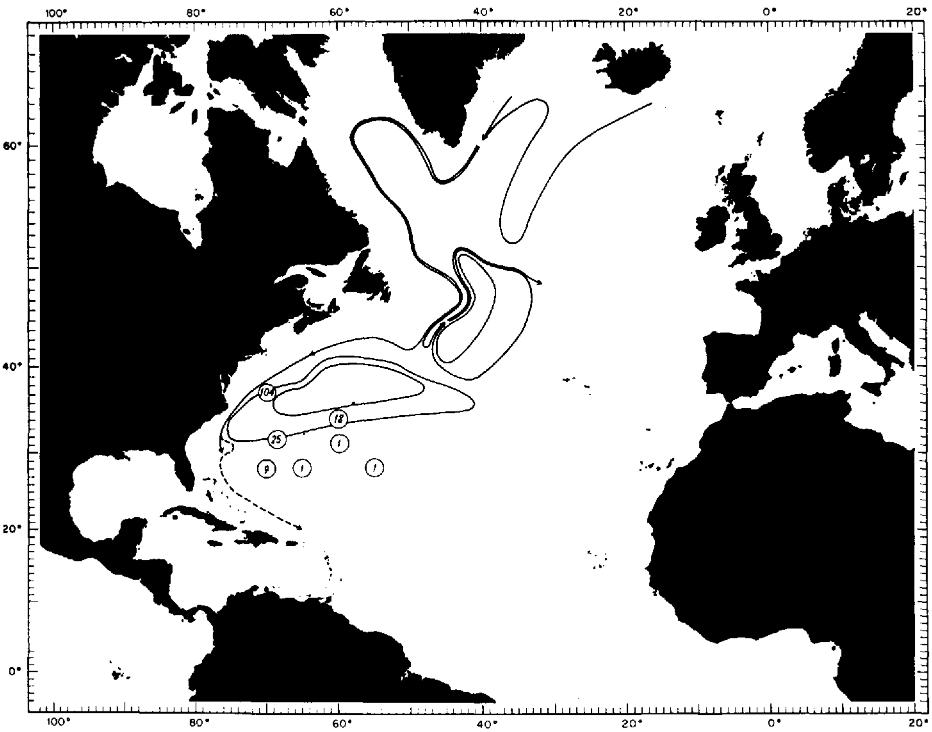


Figure 1. Previous estimates of abyssal eddy kinetic energy (enclosed in circles, units $cm^2\ s^{-2}$) superimposed on (selected) transport streamlines according to Worthington (1976; Fig. 11, p. 35) for the general circulation of the North Atlantic at potential temperatures less than 4°C. This is a modified version of a similar figure by Schmitz (1976a). The transport streamline north of the subtropical (recirculation) gyre is associated with the Deep Western Boundary Current according to Worthington; the dashed continuation is its southerly extension following Wunsch and Grant (1982), except that the jog near 30N is associated with the *Blake-Bahama Outer Ridge (see text).*

the eddy field and the location of the general circulation. There are both agreements and disagreements between Worthington's model and, for example, moored instrument results (Hogg, 1983; Schmitz, 1980).

In Figure 1, and for several figures to follow, values of K_E (in $cm^2\ s^{-2}$) are shown enclosed inside geometric symbols centered at the observational site; circles are uniformly used for the original estimates by S76. Figure 2 is a plot that is analogous to Figure 1 but based on all the data in Table 1, with new K_E estimates relative to S76 shown mostly in squares but sometimes in triangles and hexagons for reasons discussed in the following. In Figure 3, the data in Figure 2 are superimposed on a similar map, except that the 4000 m bottom topographic contour is shown instead of transport

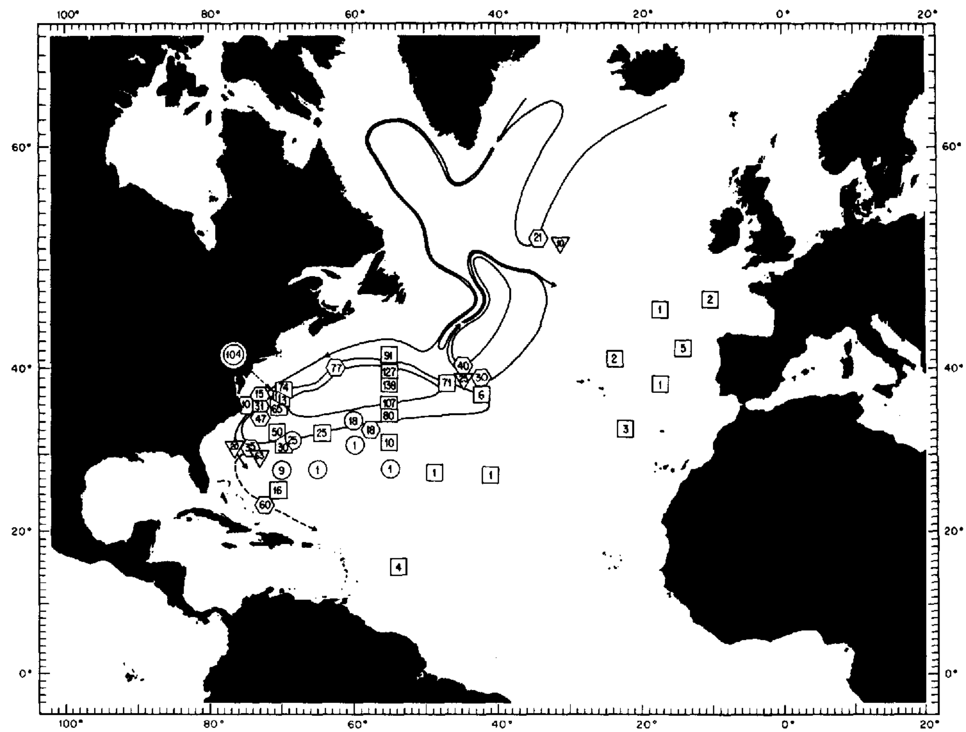


Figure 2. A chart of the North Atlantic with all existing estimates of abyssal eddy kinetic energy (K_E) superimposed on general circulation indicators identical to those used in Figure 1. K_E values (units $cm^2\ s^{-2}$) are displayed inside circles if entered on Figure 1 as well as this figure. Results that are more recent are contained in squares except for special sites denoted by hexagons and triangles (see text).

streamlines. In Figures 1 and 2, the location of the axis of flow of North Atlantic Deep Water (hereafter NADW) along the western rim (near 4000 m depth) of the North Atlantic has been augmented somewhat (as denoted by a dashed line) relative to Worthington (1976; Fig. 11, p. 28). First, this *D*eep *W*estern *B*oundary *C*urrent (DWBC; see Hogg, 1983) has been shown to pass through a recent array near 30N (discussed below), as observed. Second, the current axis has been extended equatorward following Wunsch and Grant (1982). This equatorward continuation is also in agreement with other recent measurements (by Schott, 1982) near 23N, as discussed in the following.

In (a) and (b) below, previous exploration of the North Atlantic eddy field is briefly discussed. Section (a) describes results starting with the *Aries* Expedition (circa 1958) and continuing until mid-1975. The observations obtained in this time frame were those used by S76 to construct an earlier version of Figure 1. In (b), eddy field

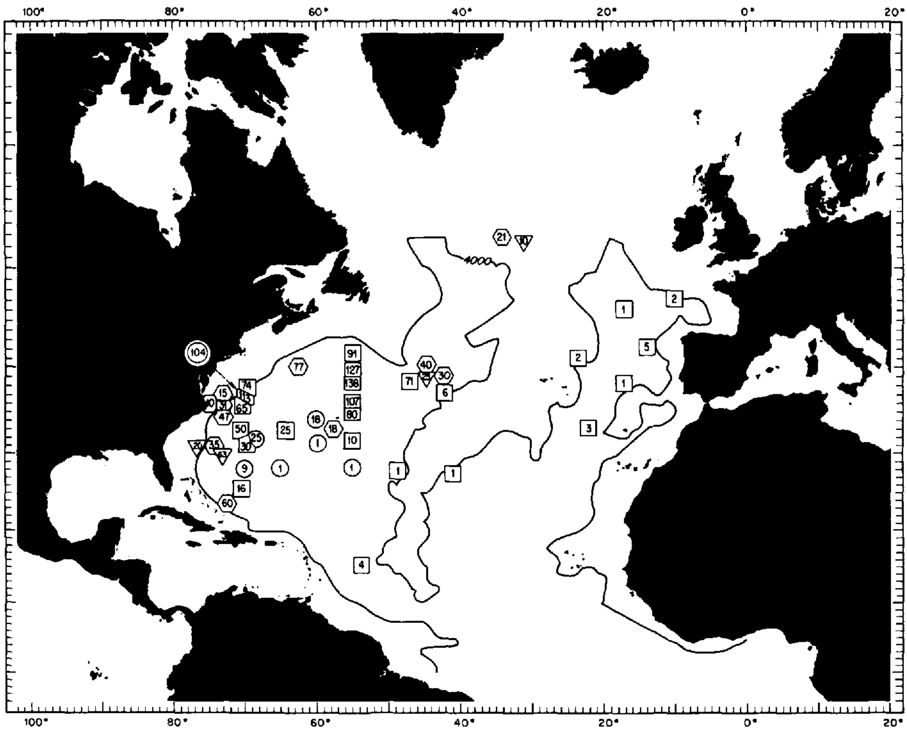


Figure 3. Analogous to Figure 2, but with eddy kinetic energy (K_E) values added to a map containing the largest horizontal scale distribution of the 4000 m depth contour according to Wunsch and Grant (1982). K_E estimates (units $cm^2\ s^{-2}$) are displayed inside circles if entered on Figure 1 as well as this figure. Results that are more recent are contained in squares except for special sites denoted by hexagons and triangles (see text).

exploration from 1975 to the present is outlined. The observations summarized in (b) are those used to expand the data base underlying Figure 1 about six-fold and obtain Figures 2 and 3, except that two very recent sets of observations are treated separately in Sections (c) and (d). The data groups examined in (c) and (d) are those critical to identifying the eddy field associated with the abyssal boundary current along the east coast of the United States and to defining the zonal scales of abyssal K_E variation in the Gulf Stream System. Contour plots are presented and discussed in (e), and a variety of observations are merged and collated.

a. Early exploration. The first abyssal K_E estimates were made in the late 1950's during the *Aries* Expedition (J. C. Swallow, 1969; M. Swallow, 1961; Crease, 1962), near the western foot of the Bermuda Rise in the vicinity of the southern edge of the recirculation associated with the Gulf Stream System. Estimates based on this neutrally buoyant float data set are comparable to but somewhat larger than K_E values obtained from data sets of quite different character acquired 10 to 15 years later. The value of 25 $cm^2 s^{-2}$ near 31.5N, 67.5W in the figures and Table 1 is an estimate based on a combination of the *Aries* observations near 4000 m depth with one four-month current meter record acquired in the early 1970s (S76).

Early efforts to measure currents with moored instrumentation, particularly near 70W, were initially reviewed by Fofonoff (1967, 1968), and Fofonoff and Webster (1971). Large amplitude abyssal current fluctuations associated with the Gulf Stream System along 70W were clearly identified for the first time by Schmitz *et al.* (1970; however this type of inhomogeneity was hinted at by the *Aries* data as well as some of the earliest moored instrument results discussed by Fofonoff, 1967). A major contribution to the 70W data base near the north of the Gulf Stream was made by Luyten (1977). Schmitz (1976a) compiled averages over all data to arrive at a K_E of 104 $cm^2 s^{-2}$ (Fig. 1, Table 1) as characteristic of the abyssal near Gulf Stream regime along 70W. The value of 104 $cm^2 s^{-2}$ is an average over about 2 degrees of latitude as well as several years of gappy data. For present purposes, this set of 70W data has been split into three latitude bins (with resulting K_E = 65, 113, 74 $cm^2 s^{-2}$) near the Gulf Stream (Fig. 2, Table 1), similar to Schmitz (1977). The latter three estimates are enclosed in a closely grouped polygonal structure in Figure 2 (and following figures), and their relation with the previous estimate depicted in Figure 1 is indicated by a horizontally offset value of the K_E = 104 $cm^2 s^{-2}$ result (in a double circle), with a dashed line and arrow indicating location.

A cooperative field effort started in the early 1970's, MODE [*M*id-*O*cean *D*ynamics *E*xperiment, see MODE Group (1978) for a summary], led to the data for the point in Figure 1 near 28N, 70W. This value of K_E (9 $cm^2 s^{-2}$), in comparison with K_E = 104 $cm^2 s^{-2}$ near the abyssal Gulf Stream, was used in the initial demonstration (S76) of an order of magnitude decrease in eddy intensity at abyssal depths moving from a mid-latitude jet toward the interior of a subtropical gyre. Some zonal exploration east along 28N and north up 60W (POLYMODE Array 1; Schmitz, 1976a, 1977) was carried out shortly after MODE (the POLYMODE program is described by Robinson, 1983, and co-authors), leading to the corresponding results in Table 1 and Figure 1. The northernmost value of K_E = 18 $cm^2 s^{-2}$ for this array is compatible with the *Aries* and) 70W data, and the three values of 1 $cm^2 s^{-2}$ (or less) along 28-31N signaled the next order of magnitude decay from MODE-like regions even farther into the gyre interior. This decay of abyssal K_E, from roughly 10 to 1 $cm^2 s^{-2}$, occurs between 70 and 65W, about 1500 km west of the Mid-Atlantic Ridge, not at the ridge as suggested by Wunsch (1983, p. 56).

b. 1975 to present. The first major addition to the sites in Figure 1 came from POLYMODE Array 2, deployed along 55W from 28 to 41N (Schmitz, 1977, 1978, 1980; Schmitz and Holland, 1982). K_E values (Table 1) for selected moorings from this array are entered in squares on Figure 2; the inclusion of all data would make the figure too busy. POLYMODE Array 2 was followed by POLYMODE Array 3 (Fu *et al.*, 1982) with groups of four or five moorings deployed near the Mid-Atlantic Ridge along 28N (labeled Clusters A and B) and in the North Equatorial Current (Cluster C) along 55W. The final POLYMODE array (associated with a *L*ocal *D*ynamics *E*xperiment, LDE) was deployed near 31N, 70W (Owens *et al.*, 1982). The values of abyssal $K_E = 1$ cm^2 s^{-2} contained in squares along 28N near 48 and 41W in Figure 2 (Table 1) are from Clusters A and B. Note that these clusters are on opposite sides of the Mid-Atlantic Ridge (Fig. 3), and that the resulting abyssal K_E estimates are the same (~1 cm^2 s^{-2}), and essentially identical to corresponding estimates along 28N as far west as 65W. That is, the abyssal eddy field at 28N is weak independently of the presence of the ridge. $K_E = 4$ cm^2 s^{-2} in a square near 15N, 55W is from Cluster C, the only abyssal estimate we have from the vicinity of the North Equatorial Current. The K_E value from each POLYMODE Array 3 cluster in Figures 2 and 3 is an average over four or five moorings. Note that Schmitz and Holland (1982) had abyssal $K_E = 9$ cm^2 s^{-2} at cluster C; 4 cm^2 s^{-2} is the appropriate low-passed value (the value of 9 contained a contribution of 5 cm^2 s^{-2} from periods of a day and shorter). The LDE array K_E values (30 cm^2 s^{-2}, in a square) are close to previous estimates from the *Aries* area. Pillsbury *et al.* (1982) have recently described independently motivated long-term moored instrument results along 70W near 32.5N. Their K_E value (~50 cm^2 s^{-2}) at 4000 m depth is also entered in Table 1 and Figures 2 and 3. Note the compatibility with data acquired earlier. A separate field program in the vicinity of Bermuda (Hogg, 1980) yields an estimate of abyssal K_E of 25 cm^2 s^{-2} there, very consistent with other measurements (this value is entered in a square near 33N, 64W on Fig. 2).

Other data sets also yield values compatible with those resulting from POLYMODE Array 2. Hendry (1982) deployed three moorings concurrently in the vicinity of one of the northern (~40.5N) POLYMODE Array 2 moorings and notes that abyssal kinetic energies (and other time averages) computed over common time intervals agree to well within expected differences. More recently, Richardson *et al.* (1981) have made 6 to 9 month moored instrument measurements at sites just north (~40N) of the Gulf Stream but at a much different longitude (~62.5W) than the locus of POLYMODE Array 2. They find (M. Wimbush, personal communication) an abyssal K_E of about 70 cm^2 s^{-2}, lower than that observed (~125–140 cm^2 s^{-2}) at similar latitudes "under" the Gulf Stream near 55W, but compatible with K_E (91 cm^2 s^{-2} in Fig. 2) at the northernmost POLYMODE Array 2 site, and quite close to K_E at the northernmost site along 70W in Figures 2 and 3 (~74 cm^2 s^{-2}, Table 1). The measurements by Richardson *et al.* (1981) were part of a program called HEBBLE (*H*igh *E*nergy *B*enthic *B*oundary *L*ayer *E*xperiments) and additional measurements in the same area have very recently been described by Weatherly and Kelly (1982) and Koenig *et al.* (1983). Their averaged K_E is 70 to 83 cm^2 s^{-2}, depending on choice of records used, and in any event quite close to the Richardson *et al.* (1981) results. A regional average of 77 cm^2 s^{-2} (Table 1) for the HEBBLE area is entered within a hexagon in Figure 2.

The results from POLYMODE Array 2 along 55W have recently been amplified and sharply extended into the upper levels of the Gulf Stream in conjunction with new SOFAR float observations by Owens (1984) and Richardson (1983a,b) (see also Schmitz *et al.*, 1981). The charts of abyssal K_E presented here are based on moored current meter data since SOFAR floats have not yet been deployed below 2000 m (nominal) and because of generally overlapping spatial coverage. Also, it was desired to work with a homogeneous and readily accessible data base. However, all existing float/current meter K_E estimates are very consistent to the extent comparable (and are most useful perhaps as complementary measurements), as evidenced by results in the references noted earlier in this paragraph as well as recent summaries by Riser and Rosby (1983) and Rossby *et al.* (1983).

An interesting new data set has been acquired by Bird *et al.* (1982). They found a somewhat unique regime for the part of the abyssal North Atlantic sampled, one where the mean (~20 cm s^{-1}) dominates the eddy field. These measurements were made on the eastern scarp of the Bermuda Rise, in the bottom 60 m. Notice how well their estimate of K_E (18 cm^2 s^{-2}, enclosed by a hexagon in Figs. 2 and 3) fits in with previously existing observations. That is, the eddy field at this location does not stand out from the ambient field. Comparably large mean currents (~20 cm s^{-1}) have been identified in the North Atlantic for the flow of NADW (Mills and Rhines, 1979; Jenkins and Rhines, 1980; see also Schmitz and Hogg, 1983), and for the flow of AABW (Antarctic Bottom Water) in Vema Channel by Schmitz and Hogg (1983), (see also Whitehead and Worthington, 1982). However, the eddy fields "seem" more "special" in NADW and AABW than for the Bird *et al.* (1982) results, in that K_E at the "thermohaline sites" clearly occupied by NADW or AABW may stand out from the regional eddy field in which these thermohaline flow regimes are embedded.

The earliest neutrally buoyant float measurements (J. C. Swallow, 1969; M. Swallow, 1961), although short-term, indicated that the eddy field in the eastern North Atlantic could be much smaller in amplitude than in the western North Atlantic. Long-term moorings were deployed in the eastern North Atlantic as part of the NEADS program (*N*orth *E*ast *A*tlantic *D*ynamics *S*tudy: see Dickson, 1983; Dickson *et al.*, 1982; Gould, 1983; Gould and Cutler, 1980). The six K_E values in squares in Figures 2 and 3 that are east of the Mid-Atlantic Ridge (and to the east and north of the Azores) came from NEADS sites as listed in Table 1 by Dickson (1983) and are definitive long-term evidence that the intensity (K_E) of the eastern North Atlantic abyssal eddy field at latitudes in the vicinity of 40N is ~1 to 5 (cm^2 s^{-2}). A more recent field program (Le Groupe Tourbillon, 1983) in the eastern basin (~47N, 15W) near the NEADS sites yields similar values of abyssal K_E ($1 \rightarrow 5$ cm^2 s^{-2}). Higher K_E estimates on the boundary (Mid-Atlantic Ridge) between the Eastern Basin and the Newfoundland Basin have been published by Schmitz and Hogg (1978) and Dickson *et al.* (1980). These results, from the Charlie-Gibbs Fracture Zone (Table 1), are entered in a hexagon and in a triangle on Figure 2 as indicators of comparatively high abyssal K_E near the ridge, in contrast to the case at 28N (Fu *et al.*, 1982), and/or as further evidence for a relatively strong eddy field in the vicinity of thermohaline flow regimes. Indeed, K_E values in the vicinity of the Denmark Straits overflow, although not from abyssal levels by numerical definition (depths there are 1500 m and less) but again indicative of the correlation between intense eddy and mean fields, are very high (~50–350 $cm^2 s^{-2}$), see Dickson (1983).

c. Recent measurements along the east coast of the U.S. A variety of new measurements have been made along the western rim of the North Atlantic, several in the vicinity of the abyssal boundary current there, here called, following Hogg (1983), the *D*eep *W*estern *B*oundary *C*urrent (DWBC). The first indications (short-term mooring results) of high intensity variability in the vicinity of the DWBC near Cape Hatteras were described by Richardson (1977). In 1977–1978 an array of four moorings (Mills and Rhines, 1979; Jenkins and Rhines, 1980; Schmitz and Hogg, 1983) were deployed for roughly a year in the DWBC (or its vicinity) along the Blake-Bahama Outer Ridge (BBOR). K_E values from the deepest (3000–5000 m) instruments on three of these moorings are entered on Figures 2 and 3 (and Table 1), the fourth adds no essential new information and introduces complexity on the figures. The highest K_E for the BBOR array (~63 $cm^2 s^{-2}$) lies just seaward of the DWBC itself, where K_E values are in the range 20–35 $cm^2 s^{-2}$.

Schott (1982) deployed several moorings offshore of the Bahamas south of the BBOR. Two of them had current meters at 3000 m: one (his number 126) exhibited a well-defined and sizeable mean flow as expected for the DWBC, very consistent with the dashed line extension of the DWBC in Figure 2. K_E at 3000 m on mooring 126 is 60 $cm^2 s^{-2}$ (entered in a hexagon on Fig. 2, see also Table 1) nearly the same as the maximum BBOR value although twice as high as BBOR values in the DWBC. The other 3000 m result from the array deployed by Schott (1982), $K_E = 16$ cm^2 just south of the MODE area, is entered in a square on Figure 2. This observation is consistent with the larger scale field and with the results from exploration with SOFAR floats (Riser and Rossby, 1983; Rossby *et al.*, 1983) south of the MODE area. The value of 60 $cm^2 s^{-2}$ associated with the DWBC stands out clearly from the gyre scale field in which embedded, somewhat more so than the results from the BBOR array.

The first long-term moored instrument observations from abyssal depths in the vicinity of Cape Hatteras were made by Watts and Johns (1982); see also Johns and Watts (1984). These results have recently been extended by observations from a new near-bottom array deployed across the DWBC along 36N (Casagrande, 1983). Of the five sites in this (36N) array, three had long-term data from abyssal depths (one mooring was located on the shelf, another site had good data for four months only). K_E values (Table 1) from these three moorings and from the Johns and Watts (1984) site are entered as a cluster of hexagons in Figures 2 and 3 (and following). The individual sites are not positioned with precision due to lack of room on the figures; and the combination of $K_E = 10, 15, 31$, and 47 $cm^2 s^{-2}$ at very close separations suggests a complex space/time structure that is neither resolvable nor critical here, probably associated with the cross-over between the DWBC and the Gulf Stream. These results are consistent with the characteristics of the K_E estimates from Richardson's (1977) shorter-term array (P. L. Richardson, personal communication). The time averaged flows are as expected for the DWBC (to the south) for most of the 36N array (Casagrande, 1983). The K_E values of 31 and 47 $cm^2 s^{-2}$ appear to be associated with the DWBC and its boundary with the Gulf Stream System, although not standing out as clearly from the ambient field as measurements near the DWBC farther south.

d. Zonal exploration near the Gulf Stream. As pointed out by Schmitz and Holland (1982), the zonal distribution of observations in the vicinity of the Gulf Stream had been minimal relative to that needed to determine the larger longitudinal scales of K_E variability there (at that time, two sites effectively), and therefore to intercompare model and observed longitudinal scales. The results on short zonal scales from Hendry (1982) tended to be independent verification of the K_E values from POLYMODE Array 2; see however, Luyten (1977). New data in the neighborhood of the Gulf Stream System from the vicinity of the Grand Banks were obtained by Fofonoff and Hendry (1984), and near Cape Hatteras by Johns and Watts (1984) (see also Watts and Johns, 1982; and Casagrande, 1983). These two new data sets allow one to determine, essentially for the first time, the zonal distribution of abyssal K_E near the Gulf Stream. An estimated K_E of 15 $cm^2 s^{-2}$, based on the data described by Johns and Watts (1984), has been selected as indicative of the Cape Hatteras area. This region was discussed further in Section (c) above, in the context of even newer data from near 36N as described by Casagrande (1983). The essential point is that in the vicinity of the Gulf Stream System, abyssal K_E near Cape Hatteras is significantly less than observed near 70W or 55W.

The moored instrument results described by Fofonoff and Hendry (1984) are from the GSE (*G*ulf *S*tream *E*xtension) array: nine moorings had instruments near 4000 m. Seven moorings were maintained by the Woods Hole Oceanographic Institution (WHOI) for about 13 months; one of these moorings contained near-botton instrumentation only. Two moorings toward the northeast extremity of the WHOI array were maintained for approximately 12 months by the Bedford Institute of Oceanography (BIO). Four data points from the WHOI array are entered in Figure 2 (as well as figures following, and also in Table 1); three of these points are based on averages over pairs of closely spaced stations. K_E values (71 and 6 $cm^2 s^{-2}$) from the extreme longitudes of this array are enclosed in squares, and values in the middle (40 and 25 $cm^2 s^{-2}$) are contained in a hexagon and a triangle. The averaged K_E for the two BIO moorings (30 $cm^2 s^{-2}$) is contained in a hexagon. The values of 25–40 $cm^2 s^{-2}$ in triangular and hexagonal symbols in Figures 2 and 3 may be taken, in comparison with the values of 71 and 6 $cm^2 s^{-2}$ at the array boundaries, as possible indicators of enhanced abyssal K_E approaching the Newfoundland Basin (as yet relatively unexplored eddy-field-wise) and of local horizontal variability near the Southeast Newfoundland Ridge (Fofonoff and Hendry, 1984). Upper level indicators indicate some continuation of an energetic eddy field into the Newfoundland Basin (Dantzler, 1977; Richardson, 1983a; Schmitz, 1981; Wyrtki *et al.*, 1976). Most recently, Hendry (1984) has described the results from long-term moorings deployed near 38N, 50W. Abyssal K_E values are close to those found by Fofonoff and Hendry (1984) about 3 degrees farther east at a similar latitude. Array-averaged K_E in the 4000–5000 m depth range is about 65 compared to 71 $cm^2 s^{-2}$ noted previously in this paragraph and contained in the figures and Table 1.

The resulting zonal distribution of abyssal K_E in the vicinity of the Gulf Stream is plotted in Figure 4, which provides the first clear-cut definition of the longitudinal scale of K_E near the Gulf Stream. Figure 4 is an adaptation and extension of Figures 11 and 12 by Schmitz and Holland (1982), containing, however, the new data as described above (the older data are denoted by solid triangles, more recent results by solid squares, model results by dots). Figure 4a, plotted against a dimensional zonal coordinate, is essentially identical to Figure 11 in Schmitz and Holland (1982), and Figures 4b and 4c, plotted against a non-dimensional zonal abscissa, are analogous to Figures 12a and 12b by Schmitz and Holland (1982), but up-dated. The data points (solid squares) in Figures 4b and 4c that are new relative to those available to Schmitz and Holland (1982) indicate how the analogous K_E values in Figures 2 and 3 (and Table 1) are estimated to be those associated with the Gulf Stream. Near Cape Hatteras $K_E = 15$ $cm^2 s^{-2}$ is chosen, with the neighboring closely spaced values of 10, 31 and 47 $cm^2 s^{-2}$ taken to indicate the influence of the abyssal western boundary current (alternatively some spatial averaging could be used). Near the Grand Banks, K_E values of 25 $cm^2 s^{-2}$ (Fig. 4b) or 15 $cm^2 s^{-2}$ (Fig. 4c) are taken as plausible averages over the small scale structure depicted by the easternmost moorings in the GSE array.

Observed K_E at abyssal depths in the vicinity of the Gulf Stream reaches its highest values between Cape Hatteras and the Grand Banks, dropping by at least an order of magnitude toward each of these locations: there is a pool of maximum K_E that is coincident with the deepest recirculating gyre as postulated by Worthington (1976) and observed directly by Schmitz (1976a, 1977, 1978, 1980) and others (see Hogg, 1983, for a summary). The model results in Figure 4 do not have the same zonal scale of K_E variation as the data (Fig. 4a) except when normalized by the zonal scale of the model mean flow (Figs. 4b and 4c). In Figures 4a and 4c, the abyssal expression of the Gulf Stream is taken to originate at 75W, and in Figure 4b at 80W. The zonal extent of the abyssal subtropical gyre for the model is 1000 km throughout; for the data, about 2500 km (80–50W) in Figure 4b and approximately 1700 km (75–55W) in Figure 4c. The reader interested in a more detailed examination of this result (which is based explicitly on one particular class of numerical models) may consult Schmitz and

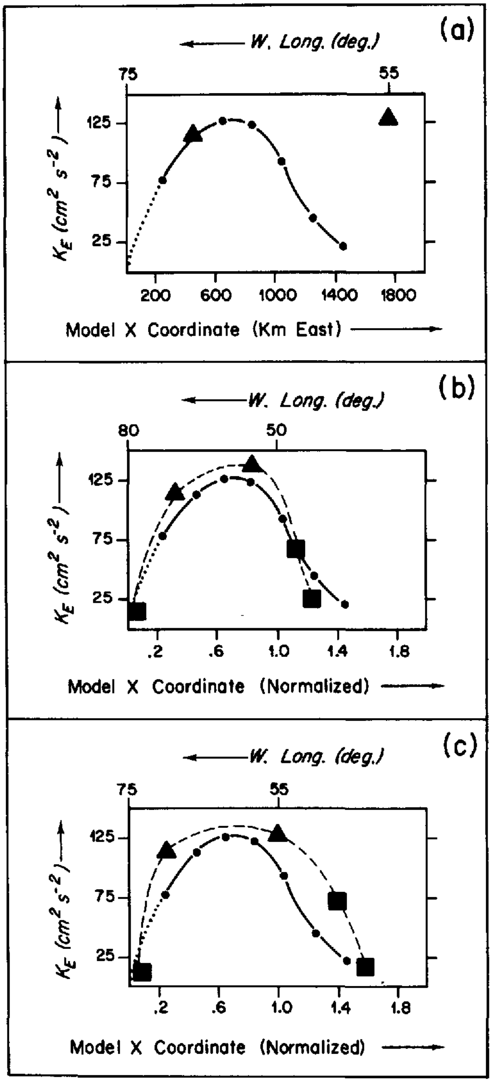


Figure 4. K_E as a function of zonal coordinate, both along the mid-latitude jet for a particular numerical model run and as observed near the Gulf Stream [adapted from Schmitz and Holland, 1982; Figs. 11 and 12; the numerical experiment used in these figures was there labeled 5.13]. The solid lines connecting dots refer to results from the model and the heavy triangles and squares connected by a dashed line refer to data points (Table 1; text): (a) The model results are plotted against model longitude and the solid points are observed values at 55 and 70W; (b) Like (a), but with results normalized by an estimate of gyre scale (as in Schmitz and Holland, 1982) and with new data points as denoted by squares; (c) Like (b), but with a different choice for gyre scale and origin. Parameters are defined in the text.

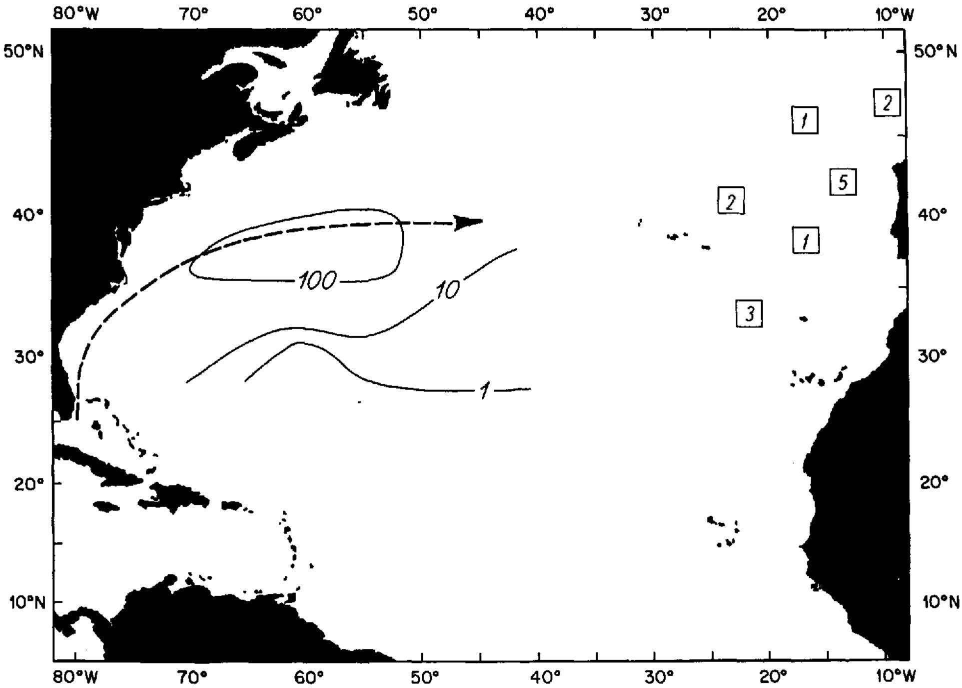


Figure 5. Order of magnitude contours of abyssal K_E (in $cm^2 s^{-2}$) for the North Atlantic. These contour lines were drawn with minimum extrapolation. The 1 $cm^2 s^{-2}$ contour is not taken across the Mid-Atlantic Ridge into the northern portion of the Eastern Basin, where the point-wise K_E estimates from Figure 2 are reproduced. The heavy dashed line is the locus of maximum kinetic energy for the surface layer mean flow, as estimated from Figure 6 by Wyrtki *et al.* (1976), see also Figure 2 in Schmitz *et al.* (1983).

Holland (1982) and Holland *et al.* (1983). The main point here is that it is now possible to draw the type of observationally-based zonal distribution plots that are contained in Figures 4b and 4c, and therefore to pursue further intercomparisons more quantitatively (in Figure 4a there are only 2 data points). The graphs in Figure 4 are not extended into the eastern basin although both model (Schmitz and Holland, 1982) and data (Figs. 2 and 3) show comparably low values there. Figure 4 is intended to be a plot along the mid-latitude jet, which might also be taken to penetrate into the Newfoundland Basin, and even northeast from there across the Mid-Atlantic Ridge. The association of intense eddy activity with the North Atlantic Current is becoming well-documented (Krauss and Kase, 1984; Krauss and Meincke, 1982) near the sea surface.

e. Contour plots and collation of results. The density of observations on Figures 2 and 3 is dramatically enhanced relative to Figure 1, enough so to allow one to draw schematic contour charts for abyssal K_E in the North Atlantic. Figures 5 and 6 contain various choices of the locations of lines of equal abyssal K_E, at order of magnitude

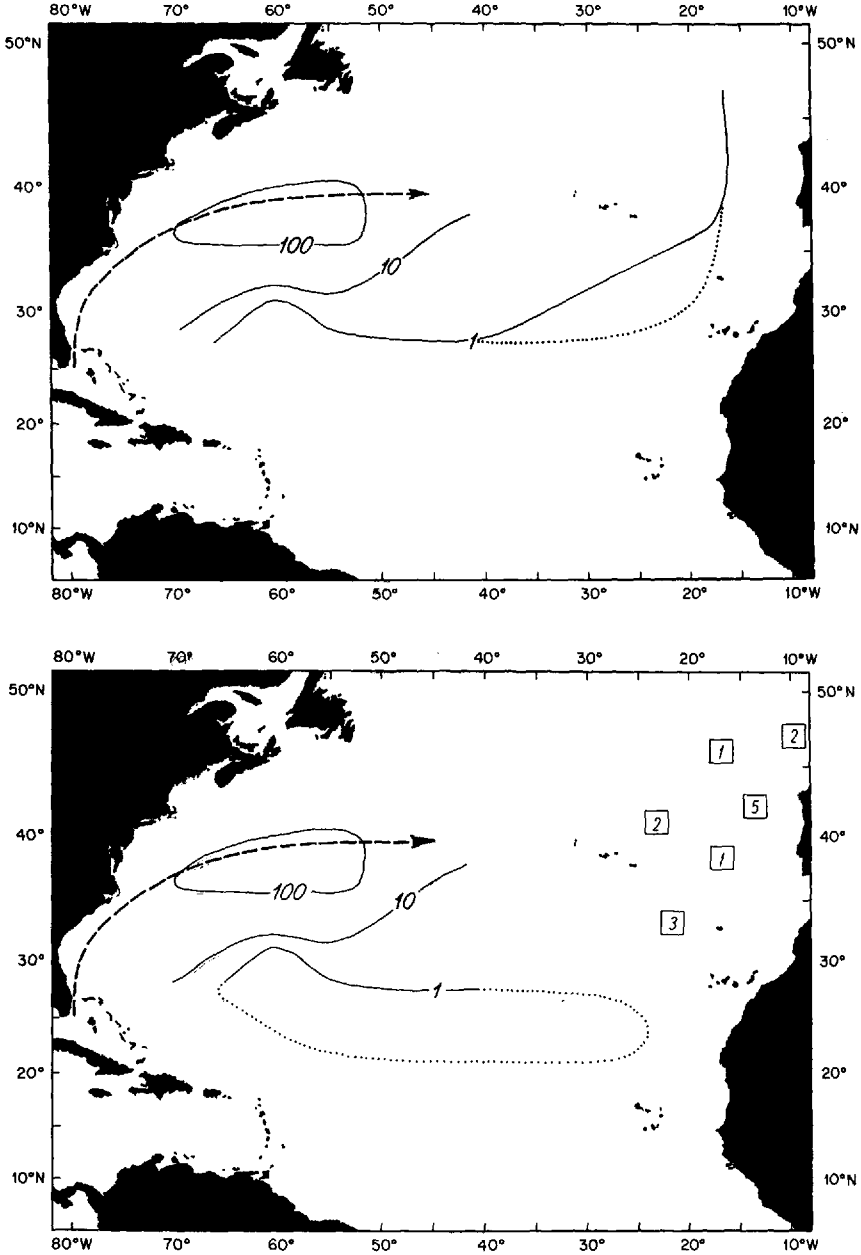
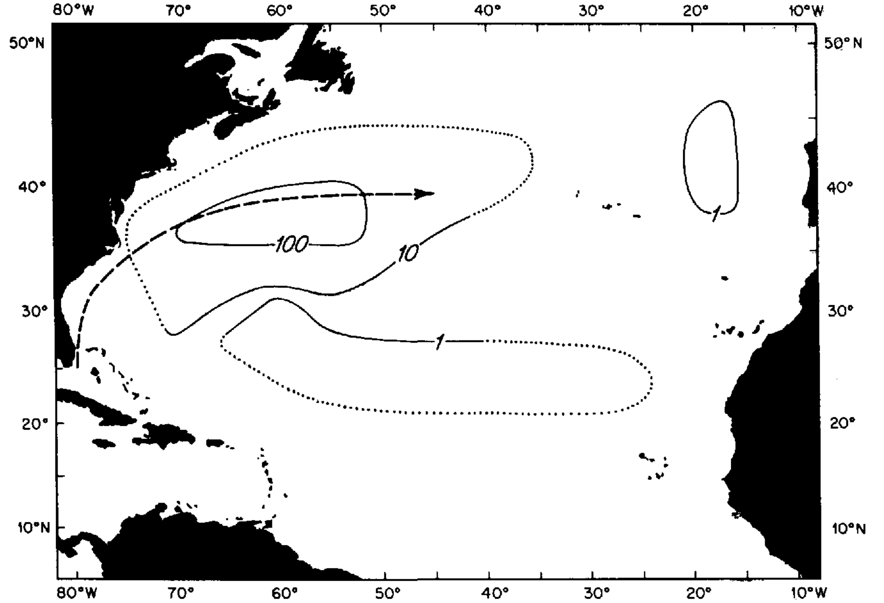
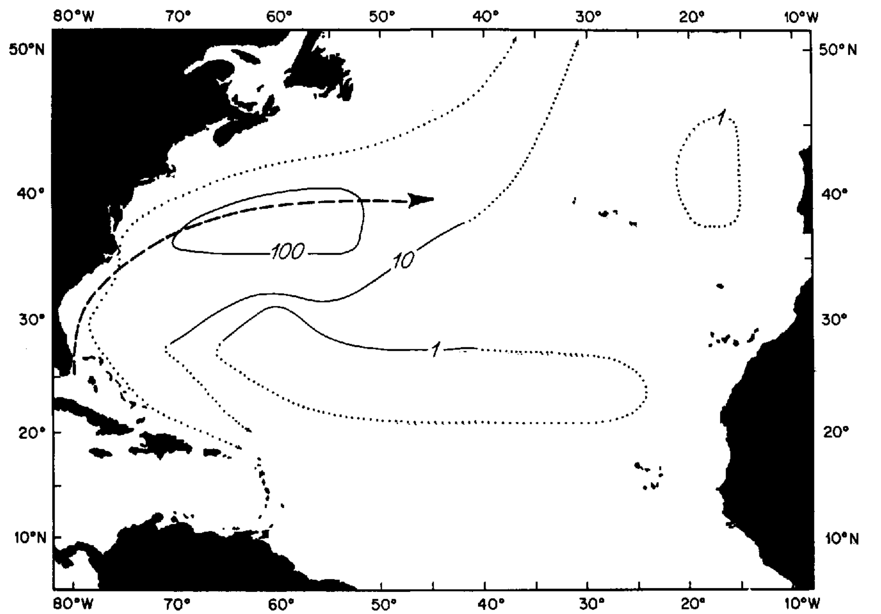


Figure 6. Order of magnitude contours of abyssal K_E (in $cm^2\ s^{-2}$), in analogy to Figure 5, but containing extrapolated contours indicated by dotted lines. The heavy dashed line is the locus of maximum kinetic energy for the time-averaged flow at the sea surface, as taken from Figure 6 by Wyrtki *et al.* (1976). In (a), two possible ways of connecting the 1 $cm^2\ s^{-2}$ contour across the Mid-Atlantic Ridge are shown. The solid line is drawn essentially linearly between





observational sites. (b) contains a different treatment of the 1 $cm^2\ s^{-2}$ contour, where an interior pool of low energy is indicated. In (c), the 10 $cm^2\ s^{-2}$ contour is extrapolated more or less symmetrically about the 100 $cm^2\ s^{-2}$ contour, and a pool of $K_E = 1\ cm^2\ s^{-2}$ is located in the NEADS area. In (d) the 10 $cm^2\ s^{-2}$ contour is shown extrapolated along the DWBC and into the Newfoundland Basin, and the NEADS area pool is presented as a dotted line.

intervals. In these figures, solid lines connect observations directly; dotted lines denote extrapolation. Figure 5 contains the contours that can be drawn with minimum extrapolation. Four more speculative choices of contour locations are shown in Figure 6. Two ways of extending the 1 $cm^2 s^{-2}$ contour from 28N into the NEADS area are contained in Figure 6a. Note that the easternmost value of 1 $cm^2 s^{-2}$ at 28N in Figures 2 and 3 is on the eastern side of the Mid-Atlantic Ridge. Alternatively, there might be a pool of low abyssal K_E in the interior of the North Atlantic Subtropical Gyre, as indicated in Figure 6b. The most arbitrary extrapolation is associated with extending the 10 $cm^2 s^{-2}$ contour, and two hypothetical examples are contained in Figures 6c and 6d. Part of the arbitrariness is associated with the definition of an abyssal level along the continental rise (and slope) where bottom depths are significantly less than 4000 m, but the major difficulties are in the vicinity of the Grand Banks of Newfoundland and into the Newfoundland Basin, as well as near the DWBC. This situation is illustrated by comparison of Figures 6c and 6d. The extension of the 10 $cm^2 s^{-2}$ contours along the DWBC and into the Newfoundland Basin is arbitrary although qualitatively consistent with what data are available, and basically meant to pose rather than answer the question. Upper-level contours do tend to penetrate into the Newfoundland Basin.

The largest K_E contours in Figure 6c and the outlying streamline in Figures 1 and 2 for the abyssal subtropical gyre according to Worthington (1976) are superimposed in Figure 7. All contours in Figure 7 are located west of the Mid-Atlantic Ridge, where it is clear that mean and eddy fields have similar horizontal scales. The exploration of the eddy field begun in the late 1960's and pursued intensely in the 1970's has led at this point to a fairly clear-cut basic geographical pattern of abyssal K_E at mid-latitudes for the North Atlantic. Early ideas (Phillips, 1966) on the significance of westward intensification of the abyssal eddy field should be re-evaluated in terms of the actual pattern of geographical inhomogeneity displayed so clearly in Figures 2, 3, 5, 6, and 7 (a point originally suggested by Phillips as well). The symmetry of the distribution in these figures is horizontally more north/south than west/east, but probably the key issue is that the intensification of abyssal K_E is connected to the location of the most energetic segment of the (mean or time-averaged or quasi-permanent) Gulf Stream System. This latter feature is a key characteristic of existing eddy-resolving numerical general circulation models driven by a steady wind field, where the fluctuating response is a result of instability processes (Holland *et al.*, 1983). With respect to the Mid-Atlantic Ridge, abyssal K_E values at 28N do not appear to be dramatically affected. Further north, in the vicinity of the Gulf Stream System, it is not yet possible to clearly separate the direct influence of the ridge on the eddy field from its indirect affect through the mean flow.

The location of the highest abyssal suspended sediment load in the world's oceans (Hollister and McCave, 1984) is roughly contained by the 10 $cm^2 s^{-2}$ K_E contour in Figures 6 and 7. It may be significant that Hollister and McCave (1984) do not find an exceptionally high suspended sediment load in the portion of the western North Pacific

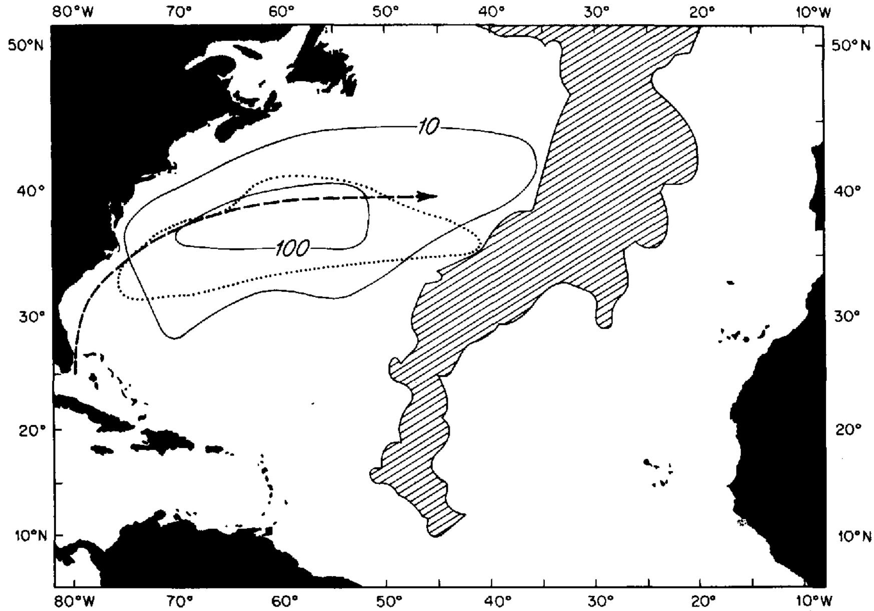


Figure 7. The largest K_E contours ($cm^2\ s^{-2}$) from Figure 6c (solid lines), superimposed on the streamline (dotted, from Fig. 1) that defines the boundary of the abyssal subtropical gyre according to Worthington (1976). The dashed line is the locus of maximum kinetic energy for the mean flow, as estimated from Figure 6 by Wyrtki *et al.* (1976). The hatched area denotes the region between the 4000 m depth contours associated with the Mid-Atlantic Ridge, taken from Figure 3.

that is analogous to the location where there is maximal suspension in the western North Atlantic, because recent physical oceanographic measurements along 152E yield a maximum abyssal K_E that is only about ⅓ of that found in the western North Atlantic (Schmitz *et al.*, 1982; Schmitz, 1984).

The relation between the distribution of abyssal and upper level K_E is brought out in Figures 8, 9, and 10. Figure 8 is an adaptation of the surface K_E chart from Wyrtki *et al.* (1976); Figure 9 is a similar map from Richardson (1983a). A recent surface K_E chart based on GEOS3 satellite altimeter data (Douglas *et al.*, 1983) has several features in common with the Richardson (1983a) map, where comparable. In Figure 9 the areas enclosed by the 2000 and 1000 $cm^2\ s^{-2}$ contours are stippled. Figure 10 is Dantzler's (1977) map of thermocline P_E [eddy potential energy density, in $cm^2\ s^{-2}$; see Dantzler (1977) for definitions]. In each case the abyssal K_E values from Figure 2 are superimposed on selected upper level contours. Both eddy and mean fields in the upper layers of the subtropical gyre have larger horizontal scales than the abyssal field but for each vertical level there is an intensity maximum associated with the Gulf Stream System, between Cape Hatteras and the Grand Banks. In the west, upper level K_E and

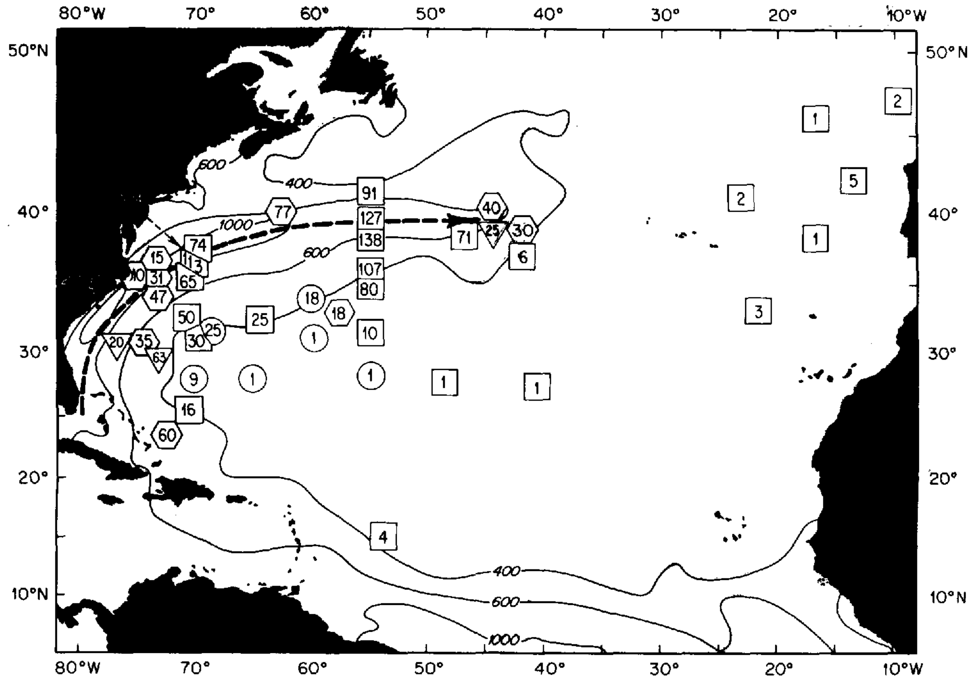


Figure 8. Abyssal K_E values from Figure 2 superimposed on selected contours of ship-drift-based surface K_E from Wyrtki *et al.* (1976). K_E is in units $cm^2\ s^{-2}$, with values contained inside circles if also entered on Figure 1. New results are enclosed in squares except for special sites denoted by hexagons or triangles (see text). The dashed line is the locus of maximum kinetic energy for the mean flow, as estimated from Figure 6 by Wyrtki *et al.* (1976).

P_E increase toward the northwest, whereas the abyssal distribution is more basically north/south intensified. The relation between abyssal and surface K_E [from Richardson (1983a); see Fig. 9] is brought out in Figures 11 and 12. The abyssal $100\ cm^2\ s^{-2}$ and surface $2000\ cm^2\ s^{-2}$ contours are roughly coincident (Fig. 11), as are the abyssal $10\ cm^2\ s^{-2}$ (from Fig. 6c) and surface $1000\ cm^2\ s^{-2}$ contours (Fig. 12). The upper level eddy intensity indicators in Figures 8, 9 and 10 tend to penetrate into the Newfoundland Basin; as does the abyssal data in the more limited sense determined by the geographical availability of the deep observations. The upper layers of the northern North Atlantic, including the Newfoundland Basin, have recently been examined intensely (Kase and Siedler, 1982; Krauss and Kase, 1984; Krauss and Meincke, 1982); the abyssal field is as yet much less well explored.

There are hints in Figure 10 of an increase of eddy activity near the North Equatorial Current. As a general rule, K_E in the subtropical gyre reaches its primary maximum near mid-latitude jets or western boundary currents in both the North Atlantic and the North Pacific (Schmitz *et al.*, 1983). However, K_E at all depths along 55W also increases approaching the North Equatorial Current Regime (NECR) from

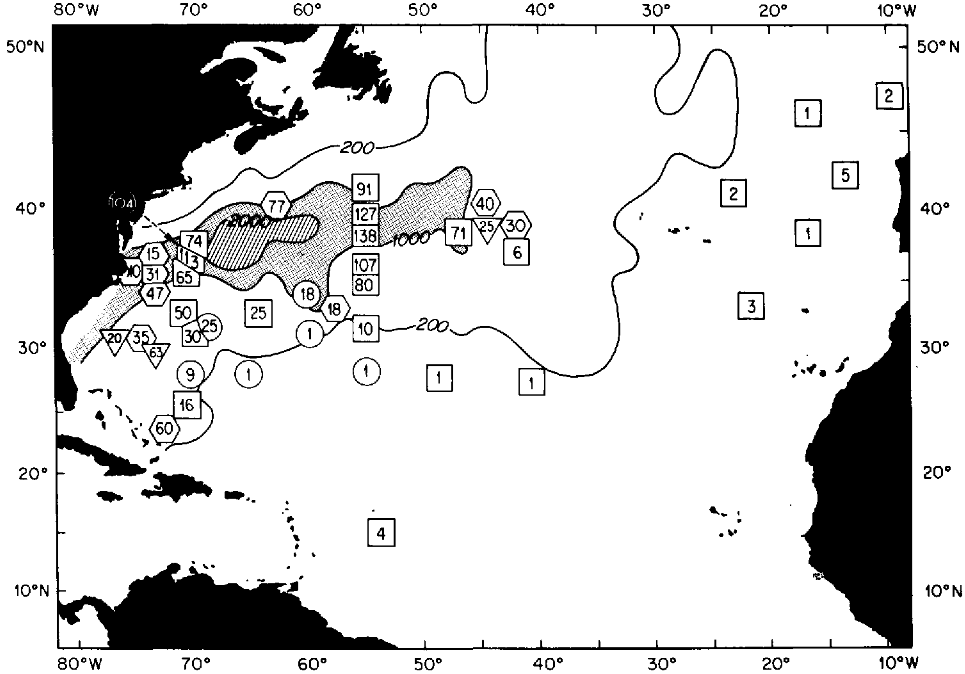


Figure 9. Abyssal K_E values from Figure 2 superimposed on selected contours of drifter-based surface K_E from Richardson (1983a). K_E is in units $cm^2\ s^{-2}$, with values contained inside circles if also entered on Figure 1. New results are enclosed in squares except for special sites denoted by hexagons or triangles (see text).

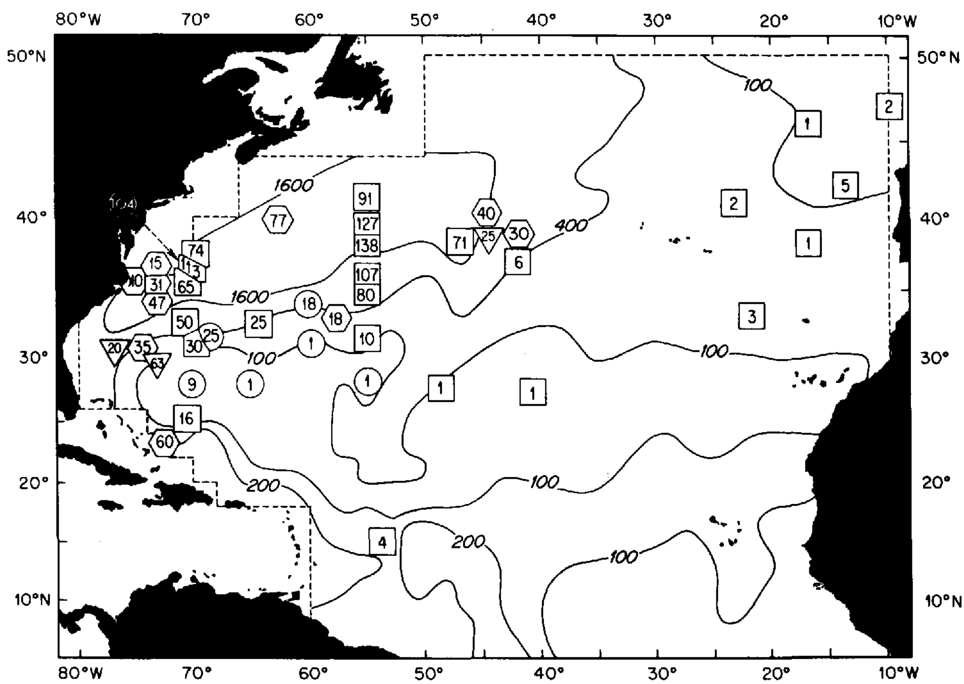


Figure 10. Abyssal K_E values from Figure 2 superimposed on selected contours of thermocline level potential energy from Dantzler (1977). K_E is in units $cm^2\ s^{-2}$, with values contained inside circles if also entered on Figure 1. New results are enclosed in squares except for special sites denoted by hexagons or triangles (see text).

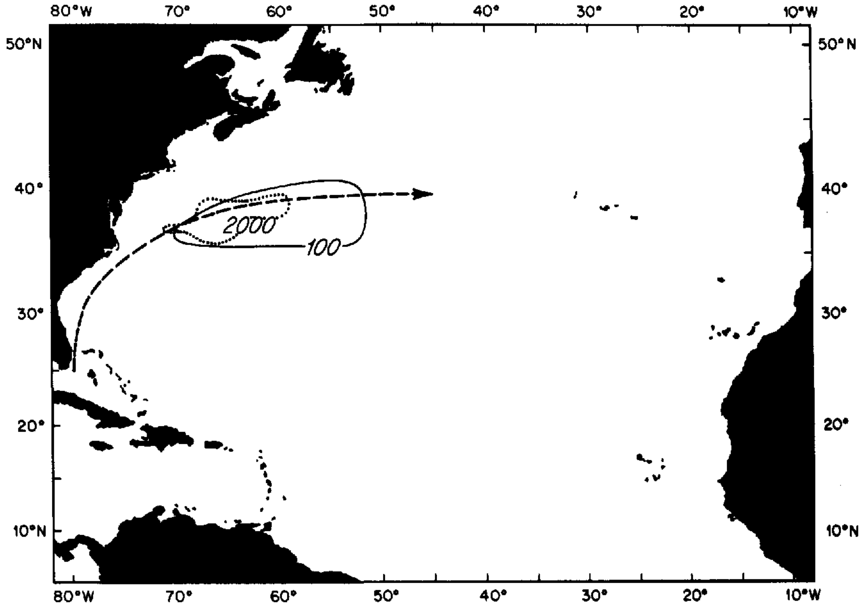


Figure 11. Superposition of the largest abyssal (solid line) and surface layer (dotted line) K_E contours (in $cm^2 s^{-2}$). These contours are extracted from Figures 6c and 9 respectively. The dashed line is the locus of maximum kinetic energy for the mean flow, as estimated from Figure 6 by Wyrtki *et al.* (1976).

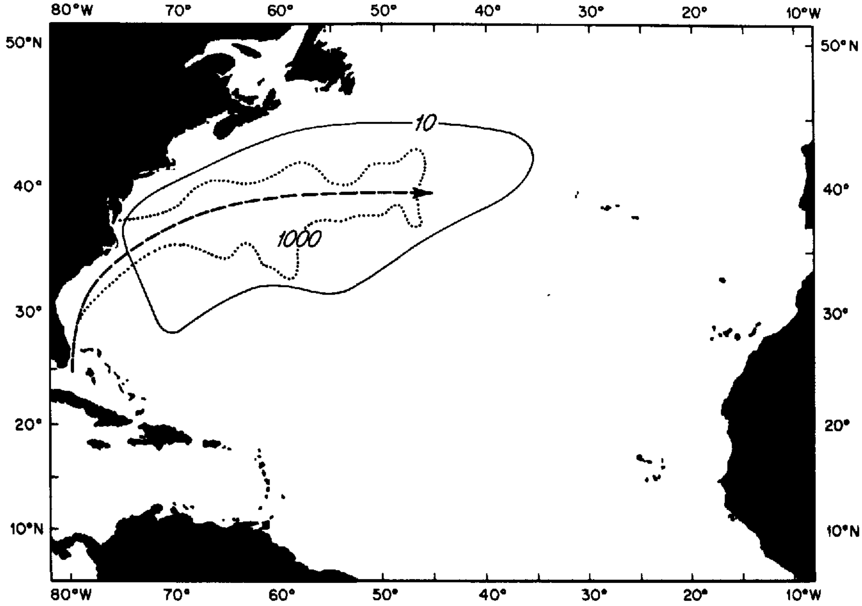


Figure 12. Superposition of the next to largest abyssal (solid line) and surface layer (dotted line) K_E contours (in $cm^2 s^{-2}$), similar to Figure 11. These contours are extracted from Figures 6c and 9 respectively. The dashed line is the locus of maximum kinetic energy for the mean flow, as estimated from Figure 6 by Wyrtki *et al.* (1976).

the interior of the North Atlantic subtropical gyre (Fu *et al.*, 1982). As indicated by Figures 2 and 3 and 8 through 10, abyssal K_E along 55W is 4 cm^2 s^{-2} at 15N in comparison with 1 cm^2 s^{-2} at 28N. The case is more clearly made for thermocline depths, where K_E varies from about 10 near 28N to 30–50 cm^2 s^{-2} (Fu *et al.*, 1982) near the NECR at 15N, consistent with the structure of the large-scale temperature field (the general circulation). Secondary maxima in K_E associated with the NECR are found in several model runs (Holland *et al.*, 1983), where the interpretation is that the NECR is a site of secondary instability relative to the mid-latitude jets and their recirculation regimes. However, the NECR regime and its eddy field have not yet been explored very much. A particularly interesting new and unique data set in this regard (Niiler and Reynolds, 1984) provides considerable motivation for further investigation. K_E was observed to actually increase with decreasing latitude (into the NECR) in the surface layers of the eastern North Pacific (Figure 13; the data points in this figure are taken from Table 1 by Niiler and Reynolds). So, the NECR is the location of the primary K_E maximum in the subtropical gyre in the eastern North Pacific. This is the only known example where K_E increases from mid-latitudes toward the south. There are, however, regional scale pools of locally high P_E in Dantzler's (1977) Figure 3 in the latitude range 10–25N (see, however, Emery, 1983), both east and west of the Mid-Atlantic Ridge (not clearly depicted in Figure 10, where only a few contours are shown). The NECR is an area where the data base is inadequate.

Data from which the K_E estimates noted above were formed also yield time-averaged currents. Mean flows along 55 to 60W in the latitude range 34 to 36N (from POLYMODE Arrays 1 and 2) were the first direct evidence (Schmitz, 1977, 1978, 1980) for the existence of an intense weakly depth-dependent recirculation associated with the Gulf Stream System. A previously unidentified current was found at the foot

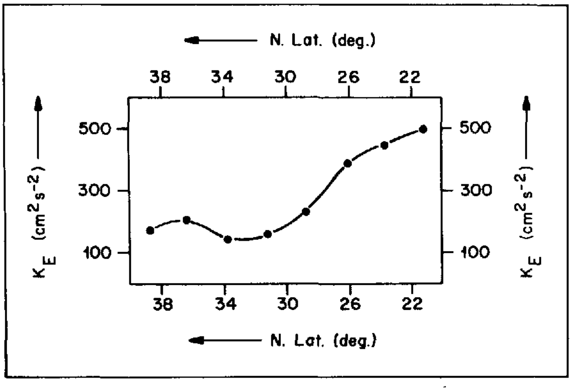


Figure 13. K_E as a function of latitude in the eastern North Pacific (near 150W), based on surface drifters. This is the only known observed example, where, at any depth, the latitudinal distribution K_E is a minimum near a mid-latitude jet (here the North Pacific Drift) and increases into another flow regime, in this case the North Equatorial Current.

of the Bermuda Rise just east of the MODE area (Schmitz, 1976b). Recent LDE (Owens *et al.*, 1982) and waste disposal site evaluation (Pillsbury *et al.*, 1982) results yield weak eastward abyssal flow in the southern segment of the Gulf Stream recirculation, as also observed along 55 and 60W (Schmitz, 1980), in possible support of some model results (see Schmitz and Holland, 1982; also McWilliams, 1983). A summary chart like those presented here, based on roughly the same set of observations but for the time averaged flow, has recently been constructed by Hogg (1984).

3. Conclusions

The first map of the North Atlantic that contained estimates of the intensity (kinetic energy) of the abyssal eddy field is now several years old. The data base has since increased from 7 to about 45 long-term sites. Updated charts are presented, containing these more recent observations, along with new methods of data presentation. The exploration of the eddy field begun in the late 1960's and pursued extensively in the 1970's has yielded at this point a relatively well defined order-of-magnitude pattern of abyssal K_E for the mid-latitude North Atlantic. The results discussed in detail here, and used to draw the first abyssal K_E contour plots for a sizeable fraction of the mid-latitude North Atlantic, are based on long-term moored instrument data. Where comparable, analogous results from SOFAR float observations are strongly supportive.

The initial indications (Schmitz *et al.*, 1970; Schmitz, 1976a) that abyssal K_E reaches a meridional maximum in the vicinity of the Gulf Stream System have been thoroughly substantiated. There are also suggestions of a secondary maximum in the vicinity of the North Equatorial Current, most pronounced in the thermocline and above relative to abyssal depths; this is a comparatively unexplored region. An essential zonal scale of abyssal variability has now been identified, placing the leading orders of magnitude in K_E that are associated with the Gulf Stream System within the region between the longitudes of the Grand Banks and Cape Hatteras. This type of result has strong implications for numerical model relevance (Schmitz and Holland, 1982); it is a prominent observational characteristic for which the class of numerical experiments examined by Schmitz and Holland (1982) have yet to account quantitatively.

It is also possible to identify an eddy field associated with thermohaline flow regimes, at least in certain areas. For example, the eddy field near the abyssal western boundary current in the North Atlantic is 30 to 60 $cm^2\ s^{-2}$ in an area where the ambient field is around 10 $cm^2\ s^{-2}$. This type of identification also stands out in the vicinity of the flow of Antarctic Bottom Water through Vema Channel.

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