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Recent moored current meter and SOFAR float observations in the eastern Atlantic near 32N

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ABSTRACT

Basic flow statistics from the two-year deployment of a mooring in the vicinity of 32N and 24W are presented, along with intercomparisons between SOFAR float results concurrent with the first year of moored instrument data. Current-temperature meters were deployed in the main thermocline (~500 m depth), in Mediterranean Water (1000–1100 m depth) along with the SOFAR floats, and at an abyssal (~3000 m) level. The float and current meter averages over a common time interval are at least roughly the same, with eddy field intercomparisons being better than those for mean flow.

Strong year-to-year variability in the time-averaged flow and eddy statistics at thermocline depths is observed. The two-year based eddy kinetic energies (K_E) are about the same as found using a variety of data taken nearby, whereas zonal mean speeds exhibit strong, comparatively short horizontal scale variability. It is pointed out that all measurements available exhibit a significant (perhaps dominant) but relatively unexplored interannual variability, not yet explicitly connected to variations in the gyre-scale circulation. Frequency distributions of K_E are peaked at the (temporal) mesoscale at abyssal depth, and K_E increases with increasing period in the thermocline. The distribution of K_E with frequency at thermocline depths is also temporally inhomogeneous, although not at mesoscale and shorter periods. Meridonal frequency distributions of K_E are peaked at the mesoscale and zonal distributions are more "red." The eddy field characteristics at this site are shown to be similar to those from other low energy regions in the North Atlantic and the North Pacific.

1. Introduction

A field program to study the low frequency currents in the Canary Basin and their relation to the Mediterranean Salt Tongue was initiated in 1984 (Price *et al.*, 1986). Moored current meters were set and SOFAR floats were deployed densely (Fig. 1) in the vicinity of 32N and 24W as one part of this large-scale effort. Our limited purpose here is to describe some of the prominent characteristics of the moored instrument time-averages, including comparisons with space-time averages based on concurrent SOFAR float data, and with historical data. There is a site from the NEADS (*N*orth *E*ast *A*tlantic *D*ynamics *S*tudy) program (Gould, 1983; Müller, 1984, 1987; Müller *et al.*, 1987; Zenk and Müller, 1988) located nearby, at 33N and 22W, where several-year duration measurements are available from both thermocline and abyssal depths.

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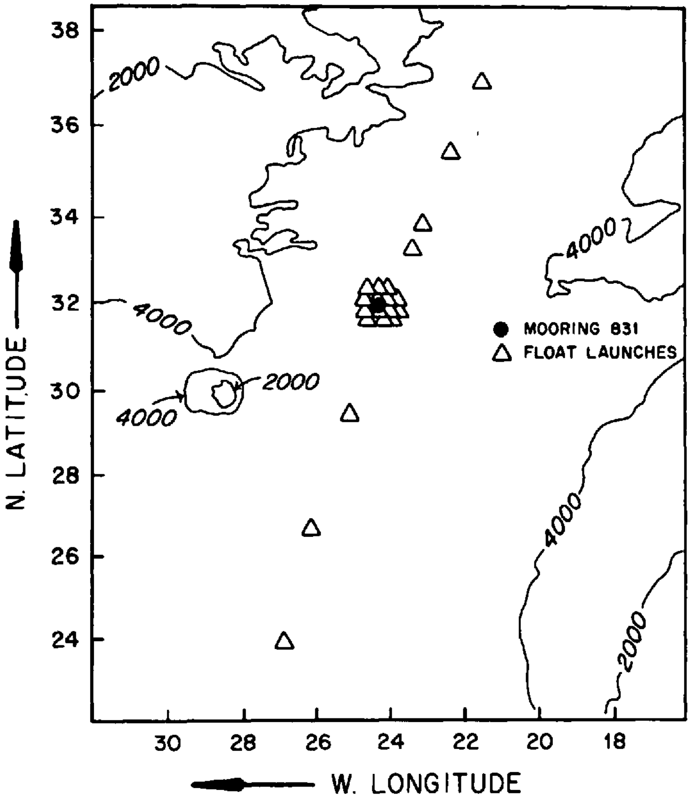

Figure 1. The location of mooring 831 along with float deployment positions, superimposed on a map showing selected topographic contours (adapted from Price *et al.*, 1986).

This general area is the location of considerable recent and on-going field work (Armi and Zenk, 1984; Gould, 1985; Käse *et al.*, 1985, 1986; Siedler *et al.*, 1987; Stramma, 1984).

2. The data base

Four moored current-temperature meters were deployed for about two years near 32N and 24W. This mooring, number 831, was set on 19 October 1984 and recovered on 4 October 1986. See Tarbell *et al.* (1987) for a detailed description of this data set; here we concentrate on various time averages and on frequency distributions. Instrument depths (nominal) on mooring 831 were 500, 1000, 1100, and 3000 m; corrected depths are 470, 970, 1070, 2970 m (Table 1). Twenty-one SOFAR floats were concurrently launched near 1100 m depth (Fig. 1), 14 in the immediate vicinity of mooring 831. The sampling strategy is discussed by Price *et al.* (1986), 1100 m depth being near the salinity maximum associated with Mediterranean Water and in the sound channel. The current meter at 970 m (1000 m design) was for redundancy at a

Table 1. Mooring 831 time averages.

Duration (day no.)	Depth (m)	$\bar{u}$ (cm s^{-1})	$\bar{v}$ (cm s^{-1})	$\overline{u'^2}$ (cm^2 s^{-2})	$\overline{v'^2}$ (cm^2 s^{-2})	K_E (cm^2 s^{-2})	$\overline{u'v'}$ (cm^2 s^{-2})
1–712	470	−2.4	0.0	24.7	15.3	20.0	0.1
1–712	1070	−1.2	0.2	7.4	4.3	5.9	−1.4
1–712	2970	−0.5	−0.1	2.2	2.3	2.3	−0.6
1–350	470	−4.8	−0.7	24.5	22.5	23.5	−7.4
1–329	970	−2.9	−0.2	9.7	8.2	9.0	−4.6
1–350	1070	−2.2	0.1	8.1	6.2	7.1	−4.1
1–350	2970	−0.7	−0.1	3.1	2.0	2.6	−0.9
351–700	470	−0.1	0.6	13.5	7.4	10.4	3.9
351–700	1070	−0.3	0.2	4.9	2.6	3.7	1.0
351–700	2970	−0.4	−0.1	1.2	2.7	2.0	−0.4

critical depth and for estimates of small scale vertical variation; note (Table 1) that this strategy paid off here (the meter at 970 m malfunctioned after 329 days). We will be intercomparing the results from mooring 831 with data from the 14 floats that were launched in a cluster near the mooring site at 32N, 24W (Fig. 1). Four floats not considered here were used to "tag" (Price *et al.*, 1986) a lens of Mediterranean Water (meddy).

The composite hydrographic environment of the float deployments (see also Käse *et al.*, 1986) in Figure 1 is shown on Figure 2a, and the vertical temperature structure in which the upper level current meters were launched is contained in Figure 2b. The upper level moored instrument time-averaged (over roughly 2 years) temperatures (with no correction for mooring motion), also entered on Figure 2b, are close to observations from the station taken when the mooring was set. Time-series data are also available from moorings 623 and 649 located near 28N and the Mid-Atlantic Ridge (~40W), on the western part of the "beta-triangle" area (Stommel and Schott, 1977; Armi and Stommel, 1983). Moorings 623 and 649 are from a cluster of moorings called POLYMODE Array III Cluster B, hereafter abbreviated PM3B. The eastern basin of the mid-latitude North Atlantic has been explored intensely in the past few years. Time-averages are available from various NEADS locations (Gould, 1983; Dickson *et al.*, 1985; Müller, 1987) most notably from a site called NEADS 1 or later KIEL276 (the "seven-year" mooring; Zenk and Müller, 1988), near 33N and 22W about 200 km northeast of mooring 831.

Each mooring is assigned a number sequentially as deployed by the buoy group at the Woods Hole Oceanographic Institution. Instruments are then identified by adding a digit to the end of the mooring number, starting from the top of the mooring. For example, 8311 is the shallowest instrument on mooring 831. Magnetic tape cassettes were extracted from the current-temperature meters, decoded, and placed in computer-compatible form. Each record was taken through standard quality control procedures, low-passed, and sub-sampled once per day. The daily values of the

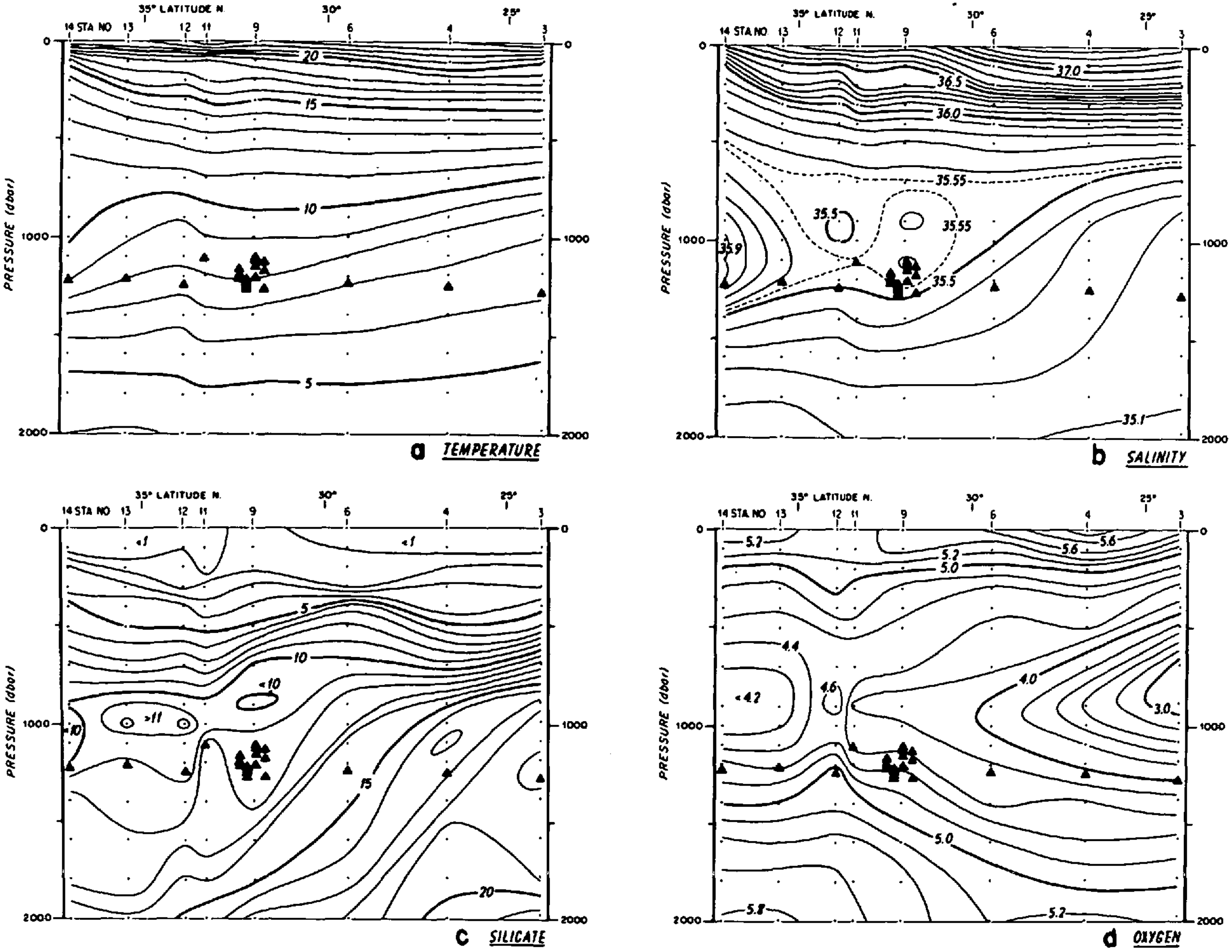

Figure 2. The hydrographic environment (adapted from Price *et al.*, 1986) for the float launches: (a) latitudinal sections as indicated, with float launches superimposed (triangles).

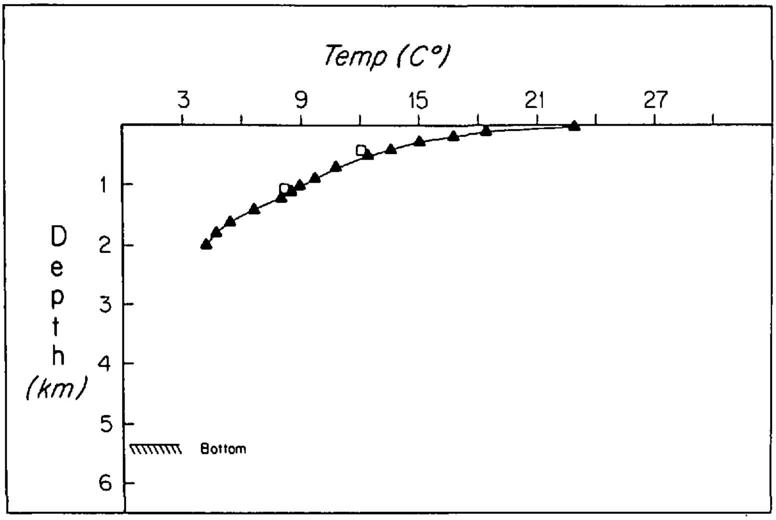

Figure 2b. The vertical temperature structure at mooring 831. Solid triangles are based on hydrographic data, open squares are two-year moored instrument averages.

low-passed velocity time series are shown in Figure 3. The records at 470, 1070 and 2970 m depths are 712 days long; starting after instrument equilibrium on 21 October 1984 and stopping on 2 October 1986. Instrument 8312 worked for only 329 days, from 21 October 1984 to 14 September 1985.

Zonal and meridional (x, y) means and variances are denoted by $(\overline{u}, \overline{v})$ and $(\overline{u'^2}, \overline{v'^2})$; the overbar signifies a time average, and a prime superscript indicates the deviation from an average. Eddy kinetic energy (per unit mass, hereafter understood) is $K_E = .5\ (\overline{u'^2} + \overline{v'^2})$. In this context "eddies" are not necessarily closed circulation cells or any spatially restricted fluctuation, but encompass the low frequency variability about the temporal mean. This includes periods longer than two days, and shorter than those (twice the record length by definition) covered by the mean.

In calculating eddy frequency distributions, the inverse of the low-pass filter initially used is applied (re-coloring) at frequencies lower than .5 cycles per day, a matter of consequence primarily for the period range near a few days. The discrete Fourier transform procedure employed assigns energy to each of the basic frequency bands $(\alpha \pm .5)\ \tau^{-1}$, where τ is the record length and $\alpha = 1, \ldots N - 1$; N is one-half the number of data days. The highest frequency $(\alpha = N)$ is a cycle per two days and encompasses only half the bandwidth of the lower frequency estimates, as does the mean $(\alpha = 0)$, which spans the frequency band from zero to $(2\tau)^{-1}$. The lowest frequency band above the mean contains contributions from the range of periods from $(2/3 \rightarrow 2)\ \tau$, "centered" at τ.

The summed energy in a few rather broad frequency bands or period ranges in the form of bar graphs is the basic time scale description used here. The notation $K_E\ (a, b)$

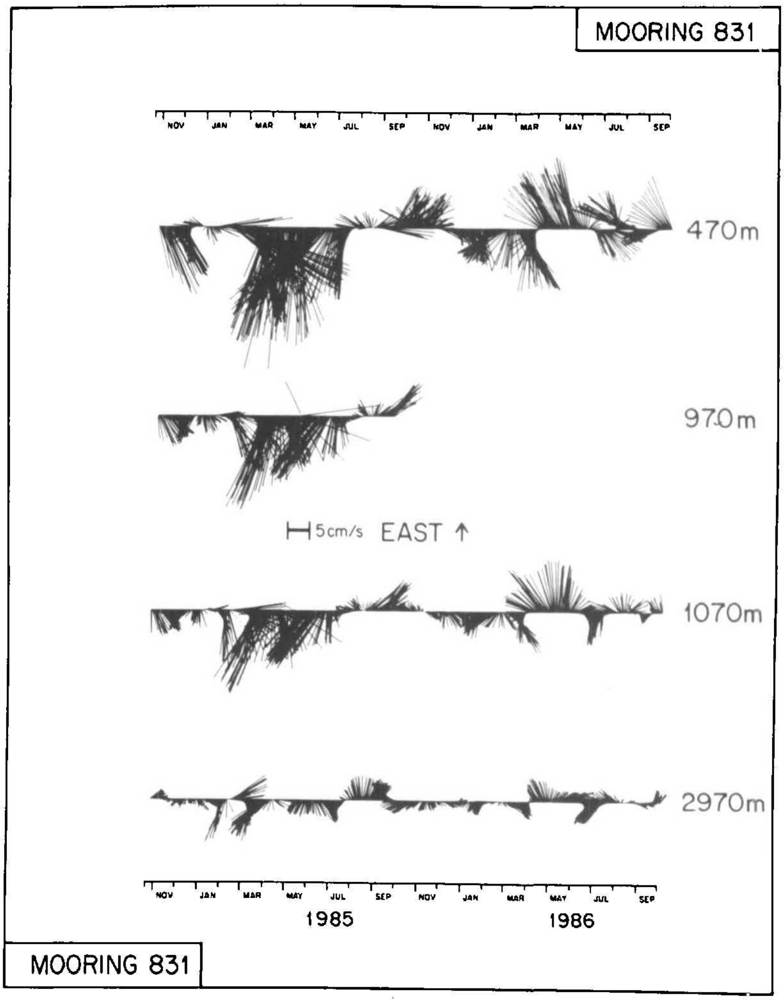

Figure 3. Time series of the low-passed daily currents from mooring 831, east up. Nominal instrument depths are noted at the side of the center line of the time series.

designates the eddy kinetic energy in the range of periods from a to b days (or the frequency band b^{-1} to a^{-1} cycles per day). The period ranges considered here are consistent with those employed, for example, by Schmitz (1978). They are K_E (20, 150), the temporal mesoscale; K_E $(150, 2\tau)$, τ = record length, secular scale; K_E (2, 20), the "high" frequency band. K_E $(a, b)/\Sigma$, where Σ is the total K_E for all frequency bands plotted, is used when "spectral shape" is being intercompared.

The basic time averages for the full 712 day series at mooring 831 are contained in the first 3 rows of Table 1. For the 3 instruments (of 4) deployed that did work for nearly two years, the records have also been split into two 1-year (actually 350-day) pieces. Standard time-averages were computed for these intervals and listed (along

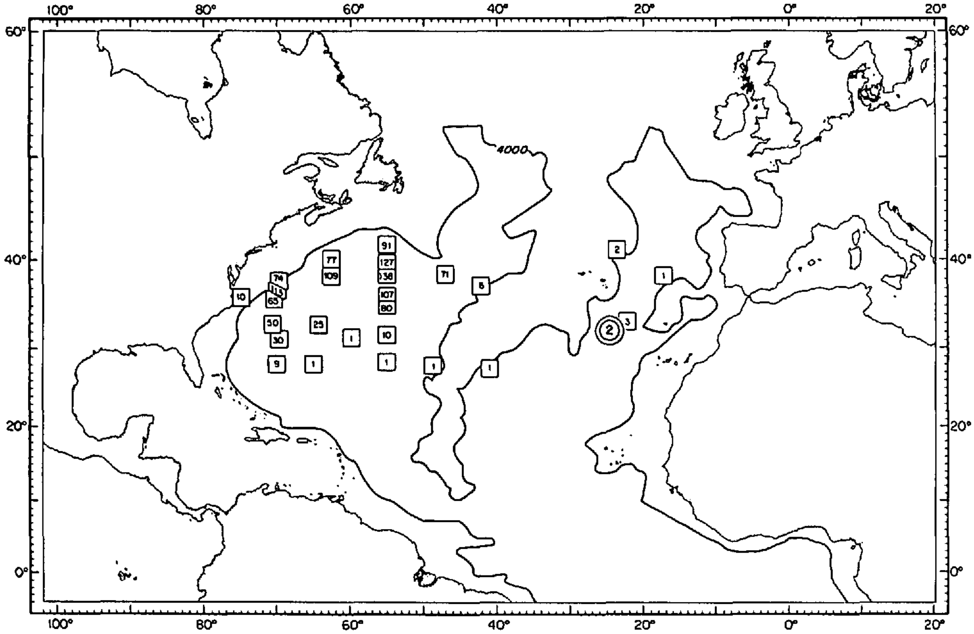

Figure 4. A chart of the North Atlantic with abyssal K_E superimposed. The solid heavy line is the 4000 m depth contour. The result for mooring 831 is entered in a double circle on an adaptation of the map due to Schmitz (1984; his Fig. 10).

with the 329-day record at 8312) in the last 7 rows of Table 1. Large changes from year to year at 470 and 1070 m depths are immediately apparent in this table, as could be inferred visually from Figure 3. The eddy field time averages at the upper levels decrease by a factor of 1.5 → 3 between the first and second years of observation, and the zonal mean flows by an order of magnitude. Results from instrument 8314 are placed in the context of abyssal K_E observations for the North Atlantic in Figure 4 where general compatibility with previous results nearby is clear.

3. Zonal mean flow

The zonal mean flow at 470 and 1070 m depths is the most notably variable from year to year of all time-averages from mooring 831 (Figs. 3 and 5 and Table 1). One can see at these depths, in Figure 3 and for the float data in Figure 6, a strong westward "jet" present for about 6 months of the first year but apparently not at other times. This 6-month duration westward jet is not a (narrow-band) annual signal because it (the jet) is not contained (Fig. 3) in the second year's data. Note that at 3000 m, there is a weak westward mean flow throughout the two-year deployment.

One might interpret the SOFAR-float data-based $\bar{u}$ distribution near 32N as a "jet" of Mediterranean Water (Fig. 6; these results are plotted at the yearly averaged float position). However, from Figures 3 and 5 it is clear that this type of $\bar{u}$ distribution

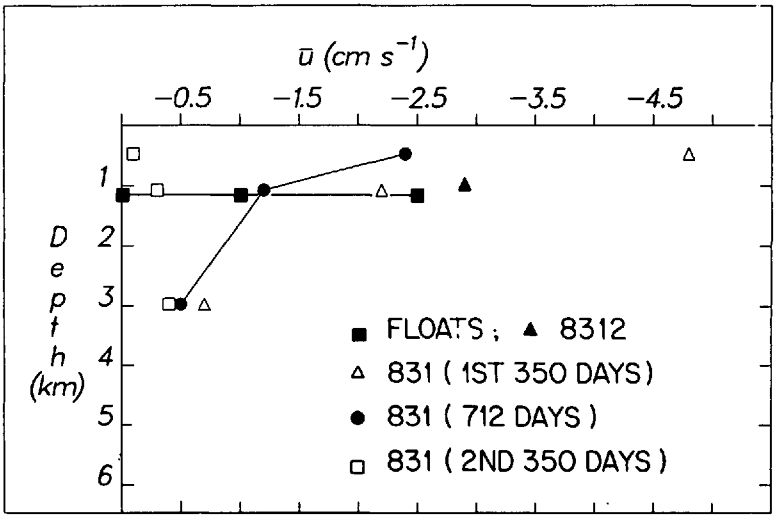

Figure 5. The vertical distribution of zonal mean flow ($\bar{u}$) from mooring 831, along with the float cluster data near 1100 m depth. Solid dots connected by a line are for 2-year averages of the moored instrument observations, open triangles and squares for averages respectively based only on the first or second year's data. A solid triangle denotes 8312 (329-day record, first year) and solid squares connected by a line indicate respectively the minimum, mean, and maximum values for the float cluster deployed near mooring 831 (32N, 24W, Fig. 1).

exists at depths other than those occupied by Mediterranean Water. This intense westward $\bar{u}$ is in fact strongest in the thermocline, and present only for six months at 32N, 24W (Fig. 3). In this context it should be noted that many float trajectories tended eastward in the latter part of their first year of deployment.

It might be tempting to account for the (year-to-year) low frequency changes in the $\bar{u}$ distribution in terms of a meandering Azores Front (Käse and Siedler, 1982; Siedler *et al.*, 1985), especially given a maximum amplitude for $\bar{u}$ in the thermocline rather than in Mediterranean Water. The westward direction of $\bar{u}$ in the first six months of the record is hard to rationalize this way, although one might appeal to a northward shift of the composite pattern described by Stramma (1984). All authors place the Azores Front to the north of KIEL276 (and therefore 831) on the average, with meanders known to reach KIEL276 (Siedler *et al.*, 1985; Zenk and Müller, 1988). The analogue to Figure 3 but with north up (Fig. 7) demonstrates that the westward currents from January to June 1985 had a southerly component to start, and then northerly, so that a westward-propagating eddy resulting from an Azores Front cut-off meander is possible, although hypothetical. But where is a "strong" westward jet in any scheme for the general circulation? There is some evidence for this "type of flow pattern" synoptically (Stramma, 1984, his Fig. 10), but not clearly so in the mean (Stramma, 1984, his Fig. 9).

The data reported by Gould (1983) and by Dickson *et al.* (1985) will be referred to

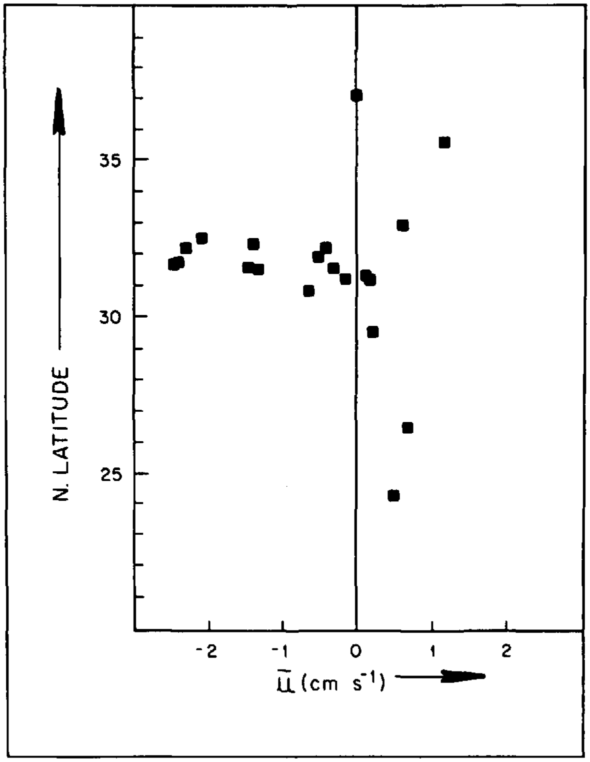

Figure 6. Mean zonal flow as a function of latitude for the floats launched at positions indicated in Figure. 1

as from NEADS 1; the longer data series from the same locale are referred to as KIEL276 (Zenk and Müller, 1988). The $\bar{u}$ distribution at site KIEL276 (Müller, 1987) is opposite in sign to 831 in the thermocline, but nearly the same at abyssal depths (Fig. 8). Mean velocities at KIEL276 based on the first two years of 3000 m data (Dickson *et al.*, 1985) are comparable to the results from 8314 in magnitude and sign. On the other hand, for the 3000 m year-and-a-half data base at KIEL277 (a morring near KIEL276) the means were about the same amplitude as at KIEL276 and 8313, but opposite sign. That is, the year-to-year variability also occurs on a short horizontal scale. The "seven-year" zonal mean flows at 1000 m (actually 2398 days) at KIEL276 are near zero (Zenk and Müller, 1988). The range of variability from deployment to deployment for $\bar{u}$ at the PM3B site (623 vs 649) is similar in total amplitude (Fig. 8) to that found at mooring 831, but also reflects a sign change. Käse and Zenk (1987) have pointed out that mesoscale horizontal variations may be a property of yearly averages of $\bar{u}$: two sites (KIEL276 and N11 or KIEL277) separated by 250 km gave yearly-averaged $\bar{u}$ values of opposite sign and roughly the same amplitude (~1.3 and 1.4 cm s^{-1}). The eastward mean is at the location (N11) nearest

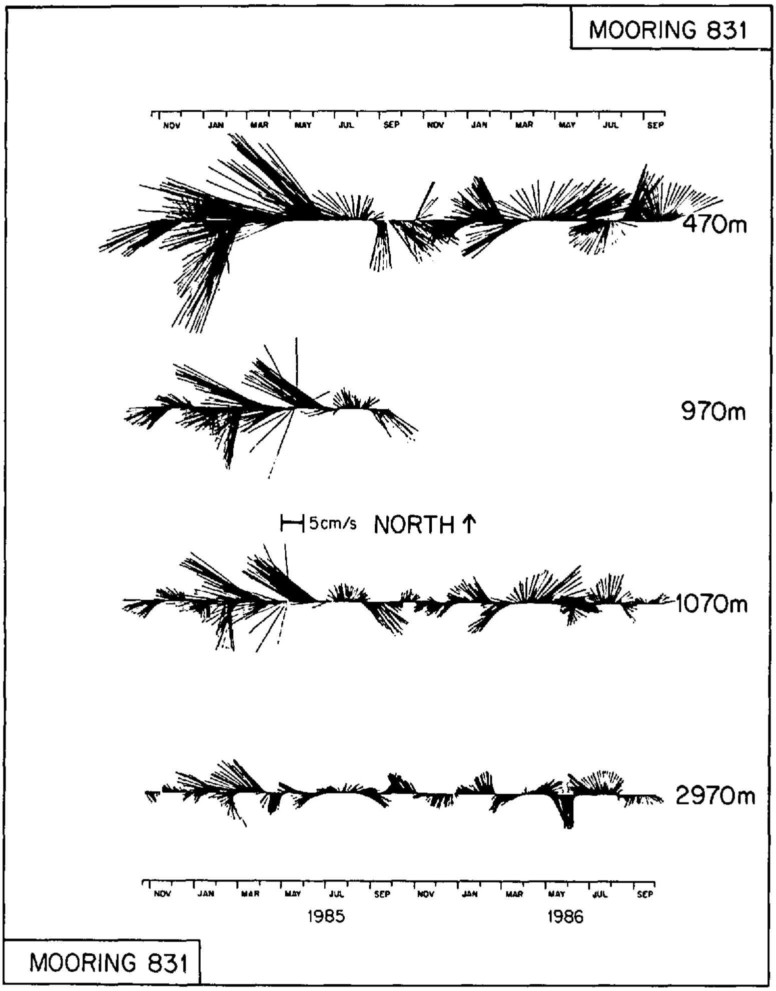

Figure 7. Time series of the low-passed daily currents from moring 831, north up. Nominal instrument depths are noted at the side of the center line of the time series.

the Azores Front (Stramma, 1984). Armi and Stommel (1983) found that the long-term variability of the baroclinic velocity shear in the "β-triangle" area was as large as the shear itself. Year-to-year or interannual variability dominates the 2400 day record at 1000 m at KIEL276 (Zenk and Müller, 1988), and the mean is very small and indeterminable. Thus, the year-to-year variation of mean flow found here appears to be the usual condition for this open ocean region.

4. Eddy kinetic energy

Vertical distributions of the key eddy statistics (or time-averages) for the two-year records are shown in Figure 9, where averages for each year are also compared. The

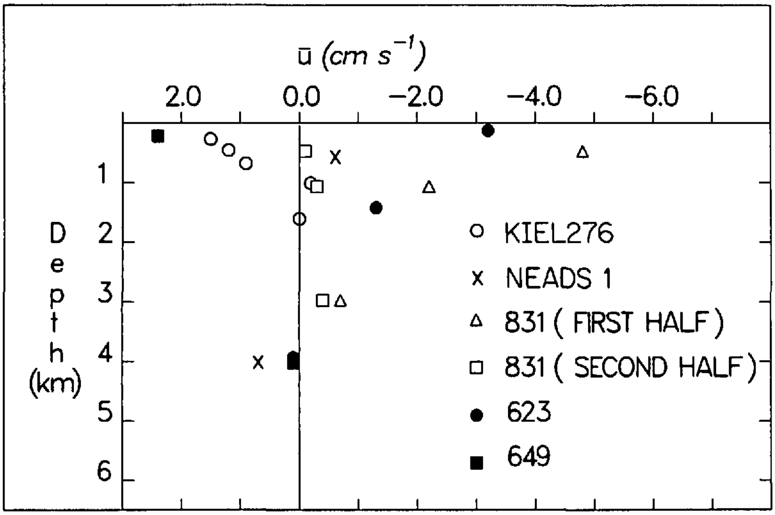

Figure 8. Composite vertical structure plots for $\bar{u}$ for 831 and a variety of sites as indicated on the figure: NEADS 1 (N1 or KIEL276) is at 33N and 22W, 623 and 649 are from the POLYMODE Array B cluster on the eastern side of the Mid-Atlantic Ridge near 28N, 41W.

intercomparison of float observations with the current meter data in Figure 9 is very good; $\overline{v'^2}$ values are within roughly 5%; $\overline{u'^2}$ is the variable where the intercomparison is poorest (25%), possibly connected to the $\bar{u}$ comparison. Differences in K_E (Fig. 9a) from year to year are relatively insignificant at 3000 m depth, but a factor of about 2 at the upper instrument. These variations at 470 m depth from year to year in K_E are not concentrated in either $\overline{u'^2}$ or $\overline{v'^2}$ (Figs. 9b and 9c). $\overline{u'^2}$ and $\overline{v'^2}$ are nearly the same for the first year, and for the second, $\overline{u'^2}$ is roughly twice as large as $\overline{v'^2}$. Both are ½ to ⅓ as large in the second year as measured in the first year. The two-year averages for K_E are notably closer to the first year's K_E than the second (Fig. 9a) because of the comparatively large mean in the first year, relative to negligible mean in the second year. That is, the mean kinetic energy for the first year appears to a large extent as eddy kinetic energy for the composite record, predominantly associated with $\overline{u'^2}$ rather than $\overline{v'^2}$ (Figs. 9b and c), since mean $\bar{u} \gg$ mean $\bar{v}$. $\overline{u'^2}$ for the two-year averaging interval is slightly larger (Fig. 9b) than for the first year and much larger than for year 2 (not between the yearly averages!) due to large differences in yearly-averaged $\bar{u}$ (i.e. one sees here a signature of significant "interannual" variability). K_E at 1070 m for 831 varies by nearly a factor of 2 from year to year, roughly consistent with the variation (about a factor of 3) observed at KIEL276 (Zenk and Müller, 1988).

The 3000 m abyssal K_E for mooring 831 (Table 1) is very close (Figs. 4 and 10) to abyssal values observed about 10 years previously (~3 cm^2 s^{-2}) at a nearby location (33N and 22W; the NEADS 1 site, see Gould, 1983) as mapped by Schmitz (1984; his Table 1, Figure 2). This is also the case for the NEADS 1 site and the first year K_E

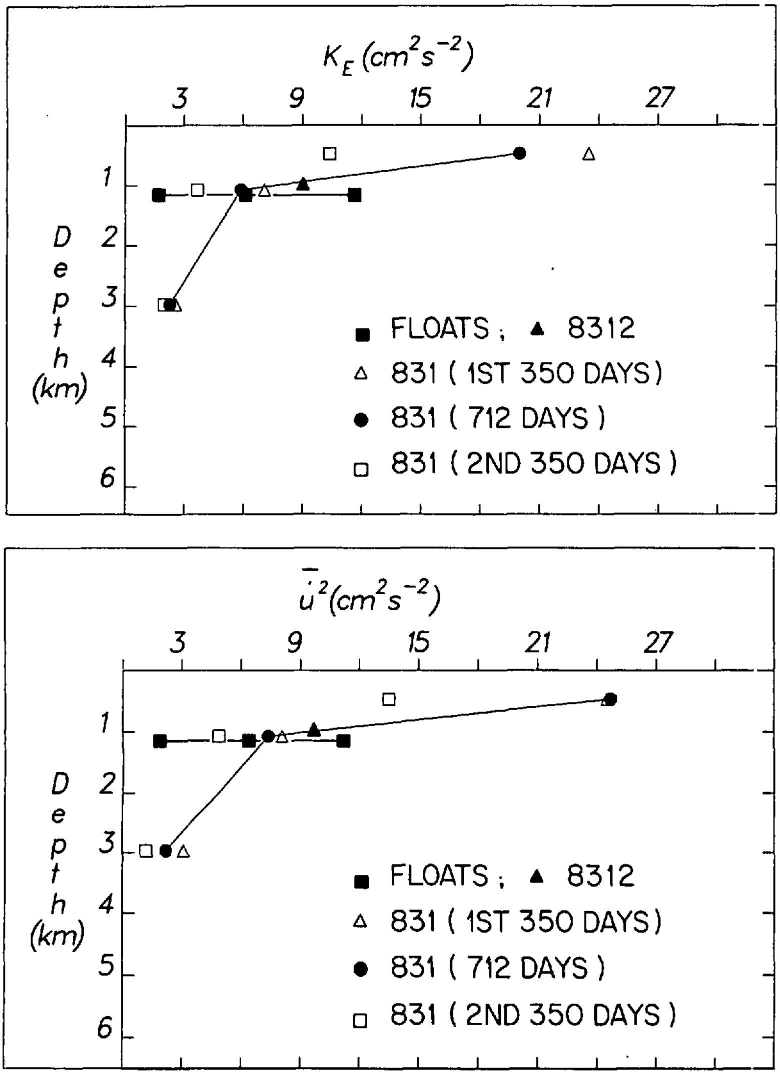

Figure 9. Vertical distribution of the eddy field time-averages, along with the float cluster data near 1100 m depth: (a) eddy kinetic energy K_E; (b) zonal variance, $\overline{u'^2}$; (c) $\overline{v'^2}$, meridional variance. Solid dots connected by a line are for 2-year averages of the moored instrument observations, open triangles and squares for averages respectively based only on the first or second year's data. A solid triangle denotes 8312 (329-day record, first year) and solid squares connected by a line indicate respectively the minimum, mean, and maximum values for the float cluster deployed near mooring 831 (32N, 24W, Fig. 1).

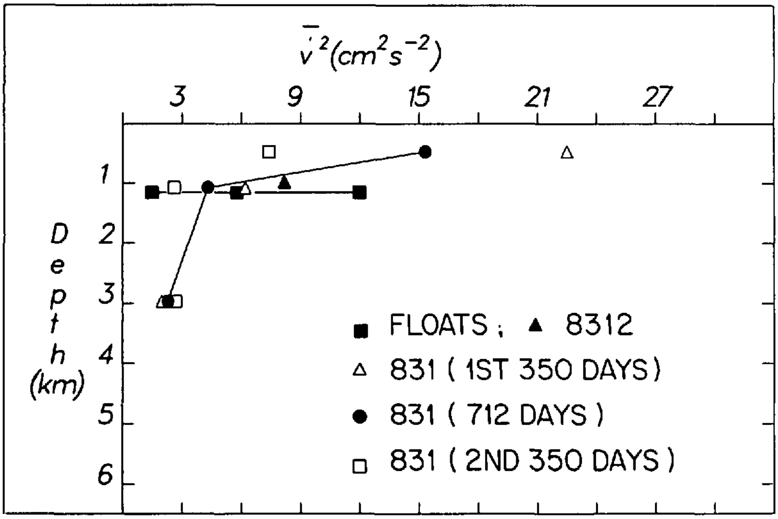

Figure 9. (Continued)

(and therefore 2-year, but not the second year results) at the upper instrument on 831 (Fig. 10). Both NEADS 1 K_E estimates in Figure 10 are based on roughly 1 year series. The vertical distribution of K_E for the KIEL276 series (Müller, 1987) is very close to the two-year results at 831. The KIEL276 and KIEL277 K_E's at 3000 m per Dickson *et al.* (1985) are 3.2 and 0.8 cm^2 s^{-2} respectively. Mooring 831 is about ½ of their

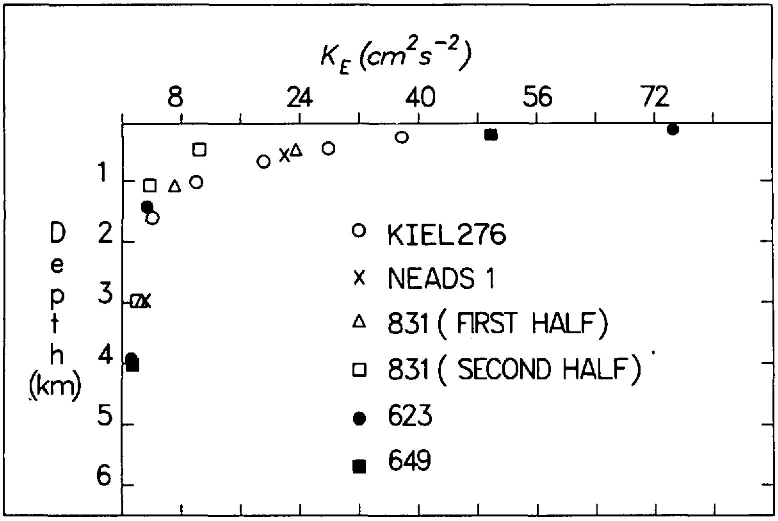

Figure 10. Vertical distributions of K_E from a variety of sites: NEADS 1 (N1 or KIEL276) is at 33N and 22W, 623 and 649 are from the POLYMODE Array B cluster on the eastern side of the Mid-Atlantic Ridge near 28N, 41W.

average, and all together could point to mesoscale horizontal variability in abyssal K_E. The data from the site mooring in the POLYMODE Array 3 Cluster B (Fu *et al.*, 1982) on the eastern flank of the Mid-Atlantic Ridge (nominal position 28N, 41W, see Fig. 4) are also entered on Figure 10. The variability from site to site (Fig. 10) is most notable in the upper kilometer of the water column and roughly the same size as the interannual variability.

Normalized frequency distributions for K_E are shown in Figure 11a for the 2-year records from mooring 831. The presentation in Figure 11a (and following spectral figures) uses either energy or normalized energy as the ordinate for 3 broad frequency bands or periods; the center band is the temporal mesoscale with periods from 20 to 150 days. There is a systematic shift in Figure 11a from maximum energy in the lowest frequency band at 500 m (nominal, record 8311) to maximum energy at the mesoscale at 3000 m (8313). This is fairly typical for ocean interior (Schmitz, 1980) or low energy areas like MODE (~28N, 70W). Frequency distributions for each 350-day record piece are shown for 8311 (~500 m) and 8314 (~3000 m) in Figures 11b and 11c. In addition to the large change in K_E from year to year at 8311, spectral shape also changes, becoming more peaked at the mesoscale during the second year. That is, neither K_E (or its zonal and meridional components) nor spectral shape are temporally homogeneous at 500 m for this data set. At 500 m (Fig. 11b), all of the significant change is at secular scale. At 3000 m the variability from year to year also shows up prominantly at secular scale (Fig. 11c). At 1070 m (8313) the spectral partitioning in frequency is similar to that observed by Zenk and Müller (1988).

Zonal frequency distributions are redder than meridional frequency distributions and more so at upper levels, again like (Fig. 12) the MODE area (near 500 m depth). Spectral comparisons with 8311 and a site in the North Pacific (7941) with a similar energy level are shown in Figure 13. The spectral shapes in Figure 13 are roughly the same, although there is more energy at higher frequencies for record 7941 (from the interior of the eastern North Pacific) and more energy at secular scale at 8311 (North Atlantic). Upper level PM3 frequency distributions are shown in Figure 14, where the zonal distribution is "red" and the meridional contribution to K_E is peaked at the mesoscale, much like MODE 500 or 8313 (Fig. 12).

5. Conclusions

Two-year duration moored instrument data have been obtained at thermocline and abyssal depths and in the Mediterranean water regime in the vicinity of 24W and 32N in the eastern basin of the North Atlantic. SOFAR floats were deployed in Mediterranean water near this mooring. Intercomparisons between the floats and current meter statistics are very good for the eddy field intensities (kinetic energies and zonal and meridional variances) but less so for the mean flow. Comparisons of the results from mooring 831 with historical data as well as results from a similar regime in the North

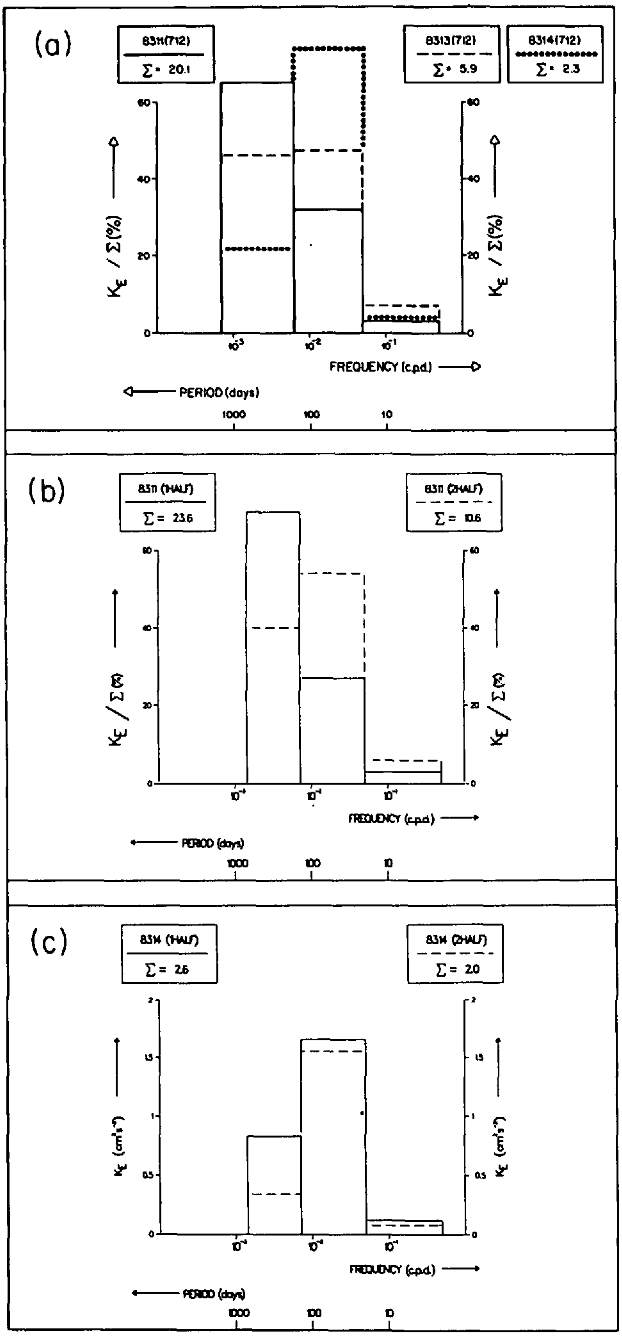

Figure 11. Frequency distributions of K_E for mooring 831: (a) Normalized frequency distributions for the two year (nominal) records. Σ indicates the total energy for the frequency bands plotted. The number in parentheses after the record identifier indicates the duration of the record (in days), depths are listed in Table 1; (b) K_E frequency distributions for the upper level instrument (470 m) for each year of observation; (c) K_E frequency distributions at abyssal depth (2970 m) for each year of observation.

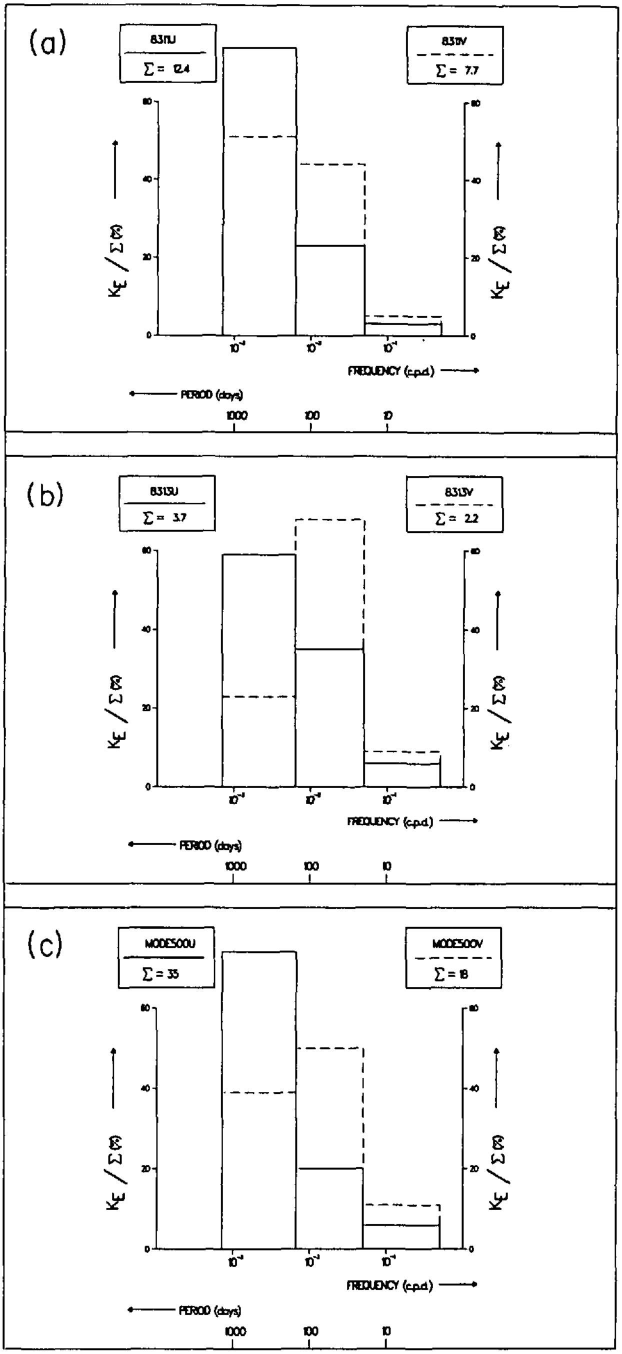

Figure 12. Normalized frequency distributions for the zonal and meridional contributions to K_E: (a) 470 m, 8311; (b) 1070 m, 8313; (c) at 500 m depth (nominal) from the central MODE site (28N, 70W).

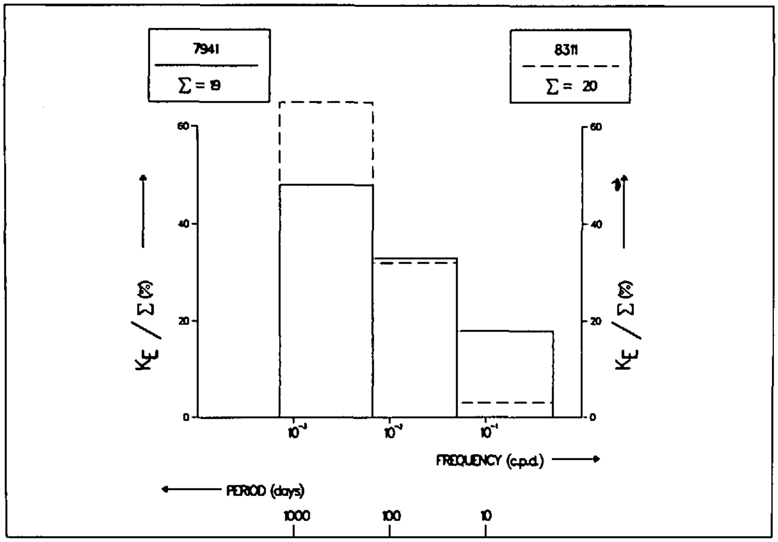

Figure 13. A comparison of the frequency distributions at 8311 (470 m) and from a similar site in the North Pacific (mooring 7941; at a nominal depth of 150 m at 35N, 152W).

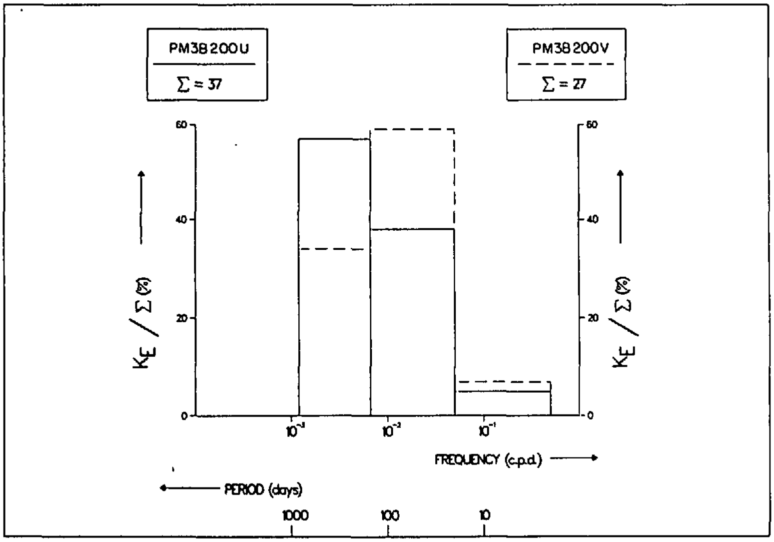

Figure 14. Normalized frequency distributions at 28N and 41W (POLYMODE Array 3 Cluster B moorings, abbreviated PM3B), for the zonal (solid line) and meridional (dashed line) contributions to K_E at 200 m depth (nominal).

Pacific suggest similar "interior" or "low-energy" flow regimes. The observed variability in mean flow and eddy statistics from year to year is strong and clear-cut.

The interannual variation in zonal mean flow observed at mooring 831 is associated with the existence in one year of a 6-month duration (nominal) westward jet at 500 and 1100 m depth, that is, not confined to Mediterranean Water. This is not an annual (narrow-band) signal; there is no similar pattern occurring in the second year of deployment; the "seven-year" record for KIEL276 near 1000 m depth is also essentially devoid of a seasonal signal (Zenk and Müller, 1988). Typical thermocline level speeds in this jet were 15 cm s^{-1}, leading to a yearly average of westward zonal speed equal to 5 cm s^{-1} at 500 m (2–3 cm s^{-1} at 1000–1100 m depths). This large year-to-year variability in mean flow is a property of all available data. It is not obviously connected to variations in position of the gyre-scale circulation, but possibly the dominant feature of the synoptic scale circulation in the eastern mid-latitude North Atlantic (see also Müller, 1987; Stramma, 1984; Zenk and Müller, 1988).

The fluctuations observed at mooring 831 are characteristic of low eddy energy regions. K_E is concentrated in the upper layer, more zonal than meridional there, and zonal K_E is largest at the longest time scales. Spectral shape is also temporally variable from year to year. In spite of these quantitative variations, comparisons with other data are quite good. Frequency distributions are reminiscent of the MODE area, that is, more peaked at the mesoscale with increasing depth and for meridional K_E relative to zonal.

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