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The MODE Site revisited

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ABSTRACT

In the 1970's, an intense physical oceanographic effort was focused on the MODE Area (centered at 28N, 70W) to study mesoscale eddies and their effect on the larger-scale longer-term (or general) interior ocean circulation. At that time there was considerable discussion as to the typicality of these results. It has become clear that the time-dependent field is horizontally inhomogeneous; eddies have a geography related to the general circulation. In some areas, significant temporal inhomogeneity (nonstationarity) has been observed, but this issue has not yet been clarified for the MODE Area.

Recently, a collective experiment to study the effect of fronts on mixed layer dynamics was carried out near the subtropical front in the North Atlantic. This note summarizes the (subsidiary) mean flow and eddy-based results from two subsurface moorings set as support for the main experiment, focusing on MODE Center (28N, 70W) where instruments at several levels from 150 to 4000 m were deployed for 20 months. Abyssal mean flow increased by an order of magnitude. The previously most stable eddy-field observable, abyssal eddy kinetic energy, changed by more than 50% from the measurement period in the 1970's to that in the 1980's. Eddy kinetic energy and mean flow in the thermocline, expected to be the least reproducible observables, hardly changed. The directionality of the thermocline eddy field is notably different, essentially reversed from the 1970's, with the meridional twice as large as the zonal variance in the 1980's. The spectral distribution in the thermocline is less "red," with the opposite tendency at abyssal depths. In summary, the MODE Area is neither particularly representative of the rest of the ocean nor are the MODE results of the 1970's quantitatively representative of measurements there ten to fifteen years later. It does seem possible, however, that many of the differences observed could be rationalized in terms of comparatively small-scale horizontal excursions of larger-scale flow regimes, notably the subtropical frontal zone.

1. Introduction

Gulf Stream Rings are the earliest discovered and best studied mesoscale eddies (Fuglister, 1972; Richardson, 1983): meanders of the Stream were also well documented sometime ago. Mesoscale phenomena in the open ocean were dramatized by the results of the *Aries* Expedition (The MODE Group, 1978). In the 1970's, an intense physical oceanographic effort was focused on a region centered near 28N, 70W (often called the MODE Area). The Mid-Ocean Dynamics Experiment (MODE-I)

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was designed to investigate open ocean eddies and their effect on the general circulation in an area southwest of Bermuda from March through mid-July 1973. These observations were generally within a 300 km radius circle centered at 28N, 70W, with a site at this location occupied quite heavily with moorings, both before and after MODE-I (The MODE Group, 1978). At that time there was considerable discussion as to the typicality of these results relative to other ocean locations. Since MODE-I, it has become established beyond doubt that the intensity (K_E, eddy kinetic energy per unit mass) of the eddy field in and near the northern hemisphere subtropical gyres reaches its maximum near the Gulf Stream and Kuroshio Current Systems at all vertical levels (Schmitz, 1976a, 1984, 1988; Schmitz *et al.*, 1983; Wyrtki *et al.*, 1976), decreasing more abruptly into the gyre "interior" with increasing depth. The long-term variability of estimates of lower order time averages (mean flow, eddy kinetic energy) depends on location and is just becoming accessible in some areas (Owens *et al.*, 1988; Zenk and Müller, 1988). The issue of "stationarity" for the MODE Area has long been a subject of debate: direct estimates of this type of variability are the focus of the following.

Recently, a collective experiment to study the effect of fronts on mixed layer dynamics (FASINEX, Frontal Air-Sea Interaction Experiment) was carried out in the vicinity of the subtropical front in the North Atlantic (Brink, 1987; Weller, 1987). In order to address the problem of open ocean wind-driven variability (Brink, 1988), and as support for FASINEX (Stage and Weller, 1985, 1986), two subsurface moorings were deployed in the western North Atlantic for 20 months, beginning in October 1984. These recent mooring results at 28N, 70W also permit examination of the decadal stability of the time-averages in the MODE Area.

2. The data

Intermediate moorings deployed in late October 1984 at (nominal) 28N, 70W (mooring number 829) and 25.5N, 70W (mooring 830) were recovered in June 1986. These positions were selected to bracket the subtropical convergence, and the vertical distribution of instruments was chosen to span the water column, with emphasis on the main thermocline. Logistics are described by Pennington and Weller (1986) and Brink (1988).

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, 8291 is the shallowest instrument on mooring 829. 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 as described by Schmitz (1988) and subsampled once per day. The zonal and meridional (x, y) means and variances are denoted by $(\bar{u}, \bar{v})$ and $(\overline{u'^2}, \overline{v'^2})$; the overbar signifies a time average, and a prime superscript indicates the

Table 1. Time averages—Mooring 829.

Record no.	Depth (m)	Duration (days)	$\bar{u}$ (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})
8291	162	596	2.6	−2.0	91.4	135.3	113.4	27.5
8293	487	596	1.7	−1.4	36.5	69.0	52.7	15.5
8294	562	596	1.6	−1.6	34.8	57.5	46.1	17.7
8296	1062	596	0.4	−1.5	10.7	15.6	13.1	4.0
8298	4062	596	0.8	−2.6	11.0	19.2	15.1	3.8

deviation from an average. Eddy kinetic energy (per unit mass, hereafter understood) is $K_E = 0.5\,(\overline{u'^2} + \overline{v'^2})$, and the mean kinetic energy is $K_M = 0.5\,(\bar{u}^2 + \bar{v}^2)$. K_u is zonal K_E and K_v meridional. In this context then, "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 covered by the mean (twice the record length by definition).

In calculating eddy frequency distributions, the inverse of the low-pass filter initially used is applied (re-coloring) at frequencies lower than 0.5 cycle 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 $(\alpha \pm 0.5)\,\tau^{-1}$, 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 $K_E\,(a, b)$ 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 (1988) or Schmitz and Owens (1979). 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.

Basic record time averages for mooring 829 are listed in Table 1, and time series of horizontal currents are shown in Figure 1. The long-term moored-instrument time series obtained in the 1970's (Schmitz, 1978; Schmitz and Owens, 1979) at 28N, 70W will be collectively called MODE C, and have 700–800 data days at each depth with several gaps. The MODE C time series is a composite of several deployments, the last of which was mooring 542. The standard depths for MODE C were nominally 500,

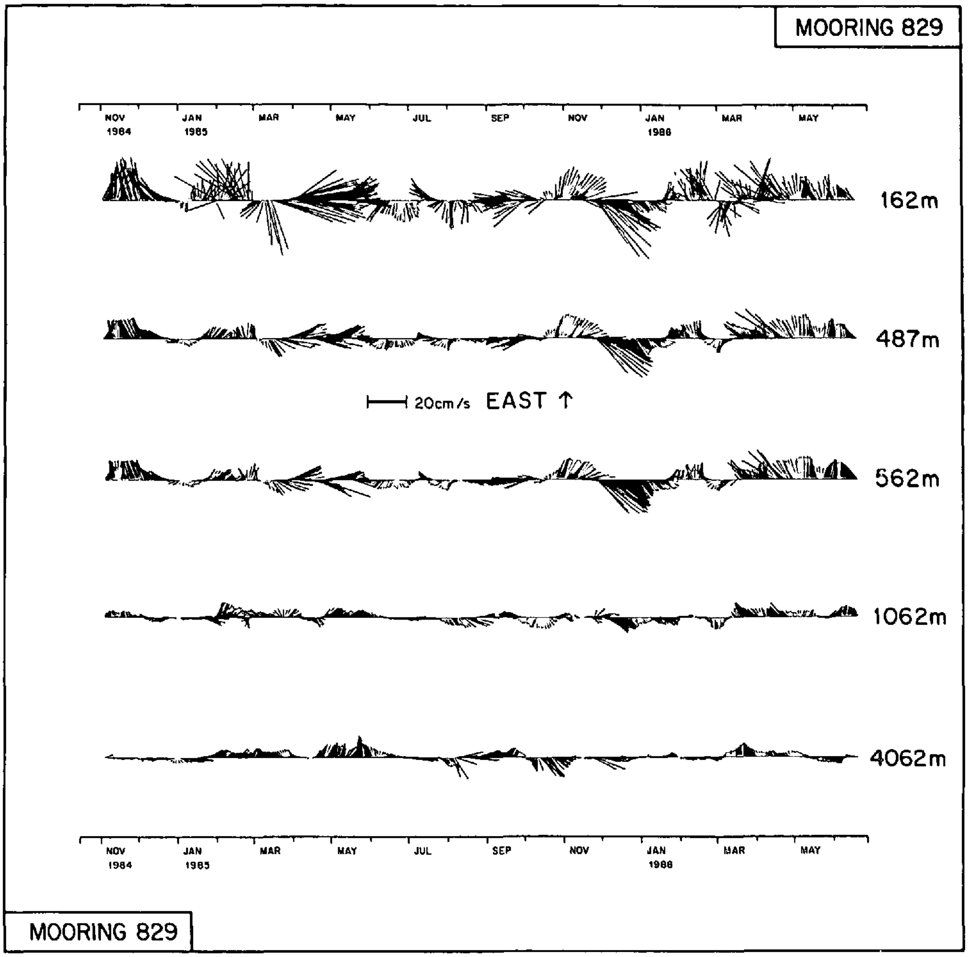


Figure 1. Time series of horizontal currents at indicated depths on mooring 829 (28N, 70W; 1980's): (a) with the vectors oriented East up, (b) North up.

1500 and 4000 m and will be abbreviated as MODE C (500), etc. Mooring 542 was the longest individual mooring deployment at that time (~9 months) and may be used for a "single mooring" intercomparison for 829; separating out to some extent the effects of gappy series statistics. Statistics for mooring 542 and for the MODE C composite site "record" are given in Tables 2 and 3.

3. Discussion

K_E in the MODE Area upper thermocline (at 8293, Table 1, 487 m depth) is about the same as for 500 m at MODE C (Fig. 2, Table 3). Since this depth (range) was the archetypical red spectrum location for the 1970's efforts, one might have expected

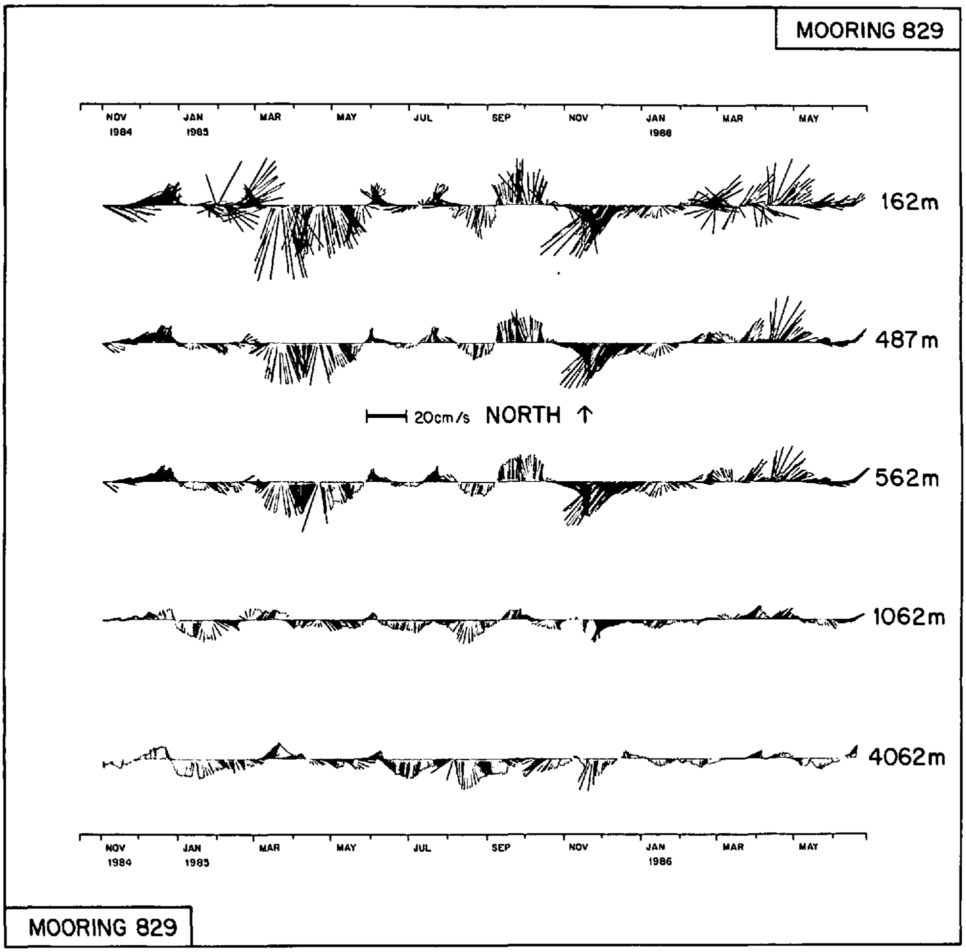


Figure 1. (Continued)

more variations and indeed 5421 itself is more different from MODE C (500) than 8293. In the MODE time frame SOFAR float observations were obtained along with those from the current meter arrays. These results were mapped on a 2° grid, at standard depths of 700 and 2000 m. SOFAR float 700 m K_E values for the 2° area centered at 28N, 70W (Riser and Rossby, 1983, their Fig. 3) are close to 829 and MODE C results, and in fact float and current meter K_E values have historically been essentially the same wherever compared consistently (e.g., Schmitz *et al.*, 1988). In Figure 2 (and Table 1) the agreement between 487 and 562 m depths on mooring 829 (8293 and 8294) is evidence for consistent observational procedure.

Surprisingly, the biggest percentage difference between 829 and MODE C (Fig. 2) is in abyssal K_E (15 vs. 9 $cm^2\ s^{-2}$ at 4000 m; 13 vs. 8.5 at 1000–1500 m), a factor of

Table 2. Time averages—Mooring 542.

Record no.	Depth (m)	Duration (days)	$\overline{u}$ (cm s^{-1})	$\overline{v}$ (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})
5421	495	268	−0.1	−1.8	78.5	45.1	61.8	−27.9
5424	1499	208	−0.6	−1.4	7.7	9.4	8.5	1.1
5427	4000	214	−0.4	0.3	7.5	10.3	8.9	6.7

about 50% (compare Tables 1 and 3). This is a dramatic and unexpected difference in light of a variety of results from the 1970's (The MODE Group, 1978). In particular, abyssal K_E was comparatively reproducible from record to record with spectrum strongly peaked at the mesoscale. Eddy kinetic energy based on float results at 2000 m depth may be compared to similar quantities at the standard current meter abyssal depths of 1500 and 4000 m where there is relatively low vertical shear below the thermocline. The SOFAR float 2000 m K_E values (Riser and Rossby, 1983, their Fig. 5) are about 10 cm^2 s^{-2} at 28° ± 1N, 70W but 14 and 17 cm^2 s^{-2} at 26° and 30° ± 1N, 70W. Thus a 2° shift (1 grid point) in the spatial pattern of K_E, which might be coupled to the location of the subtropical front (or southern boundary of the North Atlantic recirculation gyre), could rationalize the abyssal K_E differences at the MODE site between the 1970's and 1980's. For a discussion and description of this front, please see Böhm (1988) and Halliwell and Cornillon (1988a, b, c). Böhm (1988) has pointed out that the major front in the "Subtropical Convergence Zone" exhibited a larger than typical northward migration during the FASINEX time frame.

The "historical spectral or frequency distribution" of K_E at MODE C and other ocean interior locations has been widely discussed (e.g. Richman *et al.*, 1977; Schmitz, 1978, 1980; Schmitz, *et al.*, 1988; Wunsch, 1981, 1983), with the canonical distributions of energy increasing with decreasing frequency ("red") in the thermocline and peaked ("blue") at the mesoscale at abyssal depths (Fig. 3). This is typical of low eddy energy regions at a variety of locations in the world's oceans, with higher energy areas having frequency distributions peaked at the mesoscale throughout the water column (Schmitz, 1978, 1980, 1988; Schmitz *et al.*, 1983, 1988). A similar presentation to Figure 3 but for 829 is contained in Figure 4, and frequency distribution for the two key depths representing thermocline and abyssal regimes (500 and 4000 m) are compared directly for the series of interest in Figure 5.

Table 3. Time averages—MODE C Site.

Depth (m)	Duration (days)	$\overline{u}$ (cm s^{-1})	$\overline{v}$ (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})
500	696	1.2	−0.4	68.9	34.5	51.7	−11.6
1500	801	−0.5	−0.6	7.9	7.7	7.8	2.4
4000	755	0.2	0.2	7.7	9.6	8.7	3.7

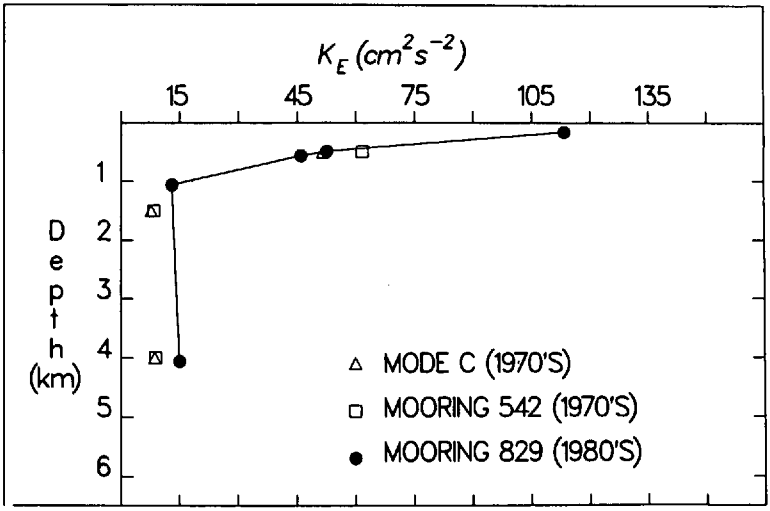


Figure 2. Vertical structure of K_E at 28N, 70W for various data sets as described in the text.

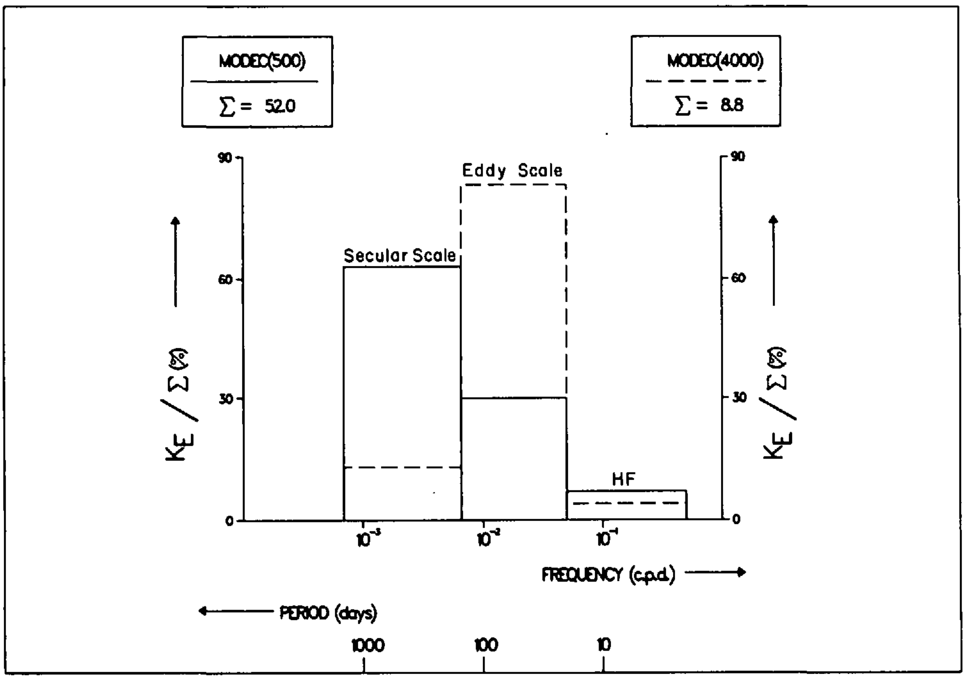


Figure 3. Normalized frequency distributions of K_E (in % of Σ = total K_E) at the key MODE C (28N, 70W, 1970's) depths (in parentheses).

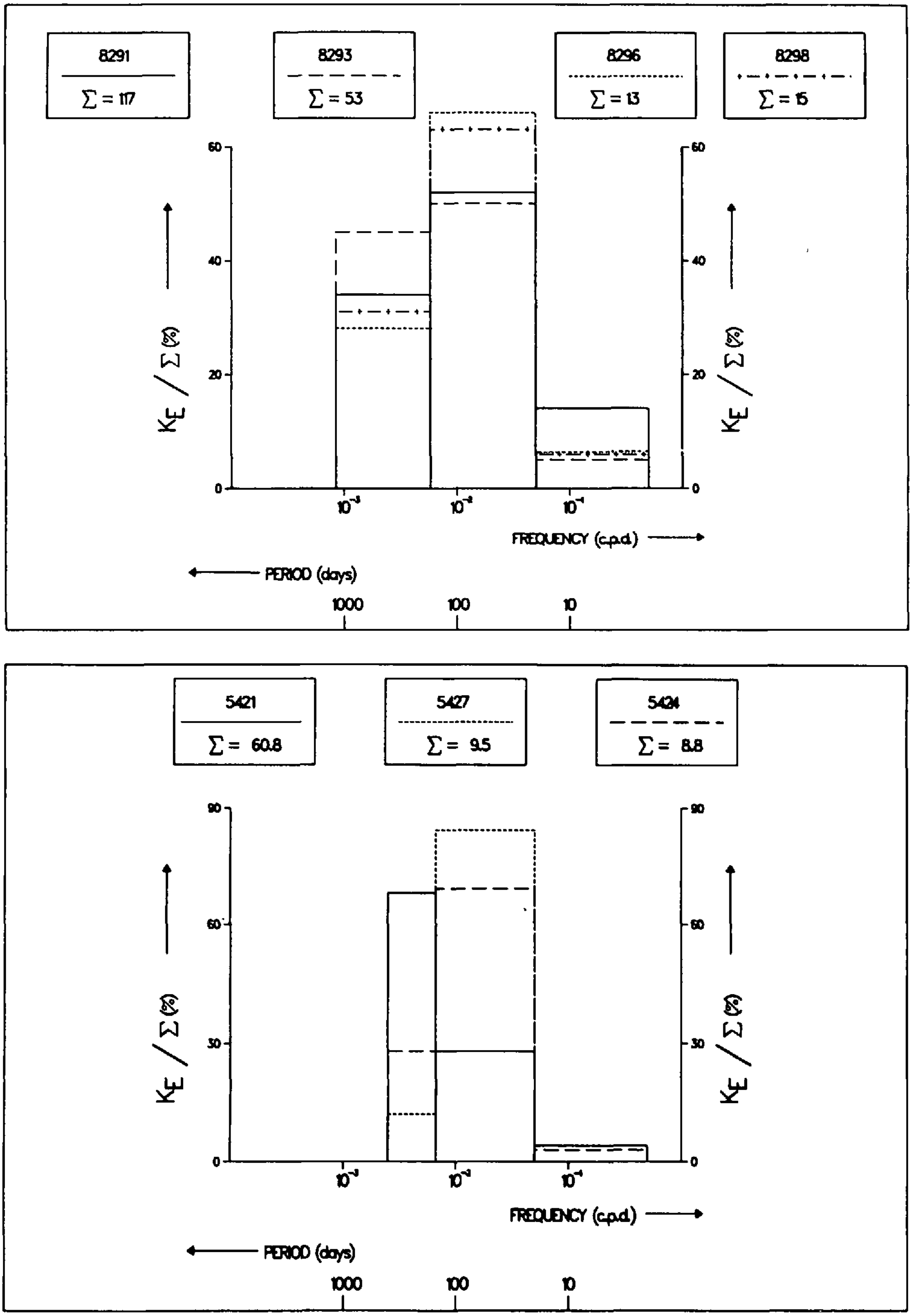


Figure 4. K_E frequency distributions, normalized as in Figure 3: (a) for mooring 829, (b) for mooring 542. Depths are 8291 (162 m), 8293 (487 m), 8296 (1062 m), 8298 (4062 m), 5421 (495 m), 5424 (1499 m), 5427 (4000 m).

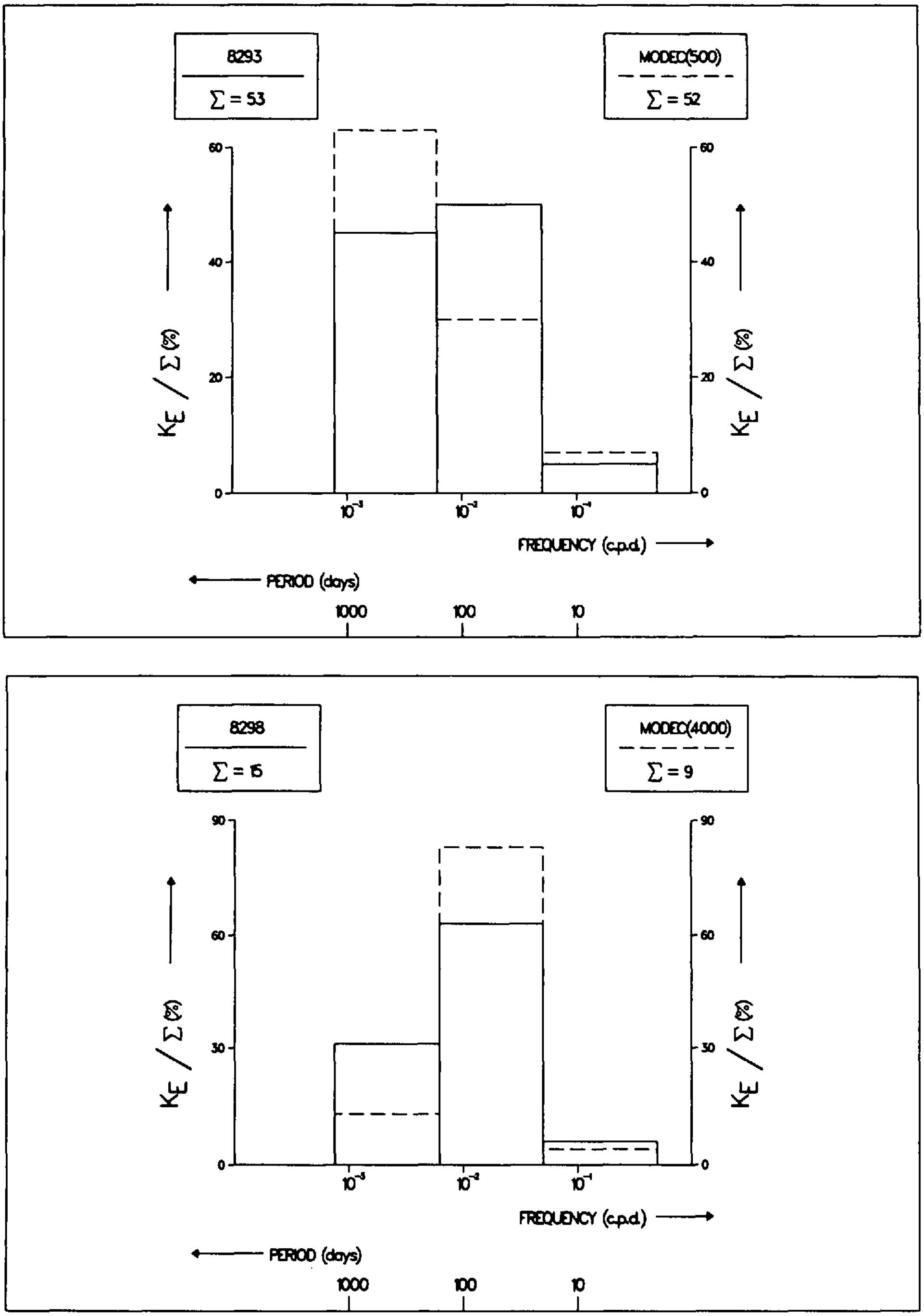


Figure 5. A comparison between the normalized K_E frequency distributions from MODE C and mooring 829: (a) 500 m, (b) 4000 m.

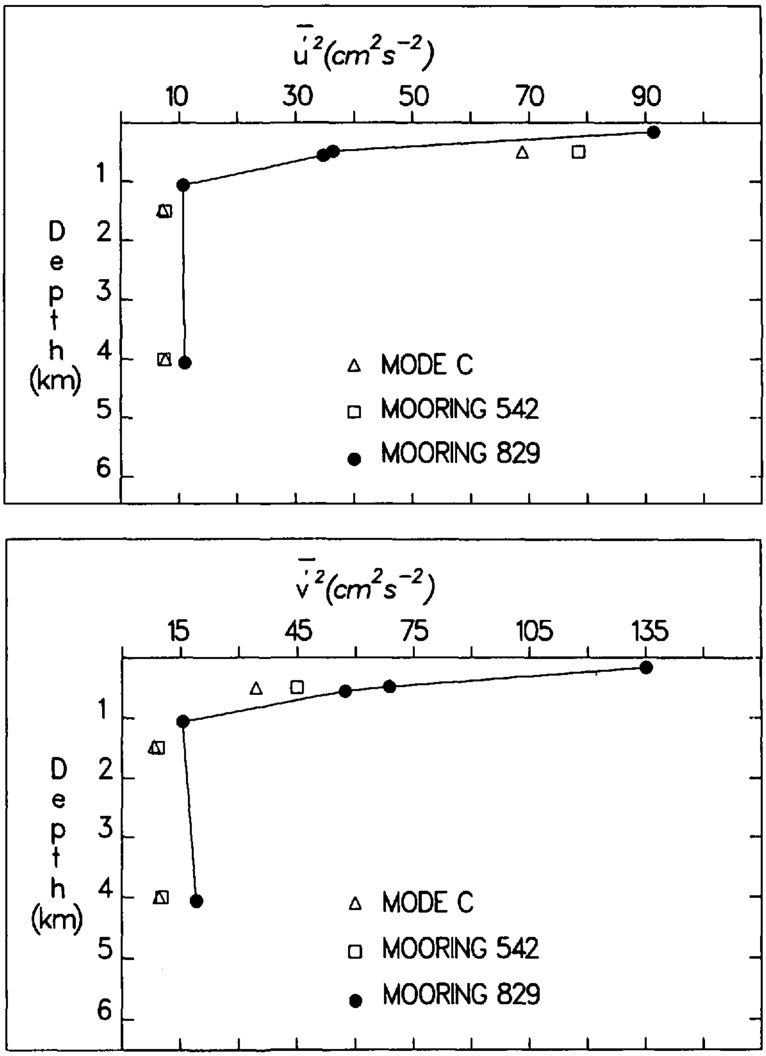


Figure 6. Comparisons of the vertical distributions of (a) zonal ($\overline{u'^2}$), (b) meridional ($\overline{v'^2}$) variances, and (c) their ratio, between moorings 829, 542 and the MODE C series.

A first glance at the normalized frequency distributions at a variety of depths for the MODE Site in the 1980's (mooring 829, Fig. 4a), would suggest weak depth-dependence compared to MODE C (1970's, Fig. 3). The 500 m K_E distribution is not red and the 4000 m results less peaked at the mesoscale for 829 relative to MODE C (Fig. 5); the decadal changes in frequency distributions occur in the opposite sense for the two key depth ranges. We can also compare distributions in the MODE Area with those from nearby sites: mooring 830, located 2–3 degrees south; and for a region

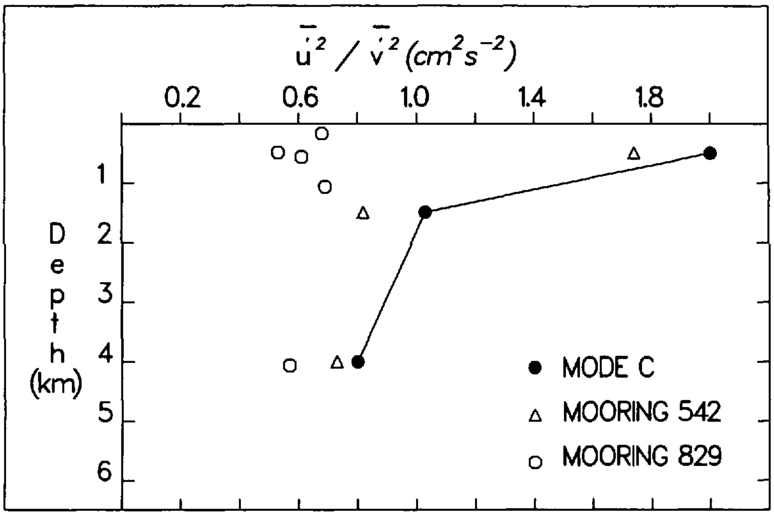


Figure 6. (Continued)

2–3 degrees north, called the Local Dynamics Experiment (LDE) area (Owens *et al.*, 1982). The 500 m spectral distributions for 8293 and mooring 8303 (thermocline) are nearly the same, intermediate between thermocline results for MODE C and the LDE region (Owens *et al.*, 1982). At abyssal depths, the normalized frequency distributions for the LDE area and MODE C (4000) are essentially the same, with 8298 less peaked at the mesoscale and correspondingly more pronounced at secular scale.

$\overline{u'^2}$ and $\overline{v'^2}$ distributions (Fig. 6) change significantly from the 1970's to the 1980's: $\overline{u'^2}$ for 829 is typically less than for MODE C and $\overline{v'^2}$ greater. Specifically (Fig. 6c) for MODE C (500), $\overline{u'^2}$ is roughly double $\overline{v'^2}$, whereas for 8293, $\overline{v'^2}$ is about twice $\overline{u'^2}$ (see also Table 1 versus Table 3). Rhines (1977) identified larger zonal than meridional variance at MODE and similar locations, especially in the thermocline, as a key characteristic for the interior ocean eddy field. However, in the 1980's $\overline{v'^2}$ is twice as large as $\overline{u'^2}$ in the upper thermocline, almost precisely reversed from what was observed in the 1970's. This is another fairly dramatic and unexpected result, possibly connected with long-term variability in the orientation of the subtropical front. Note that the ratio of $\overline{u'^2}$ to $\overline{v'^2}$ was also found to be comparatively barotropic (Fig. 6c) in the 1980's (mooring 829) as opposed to the 1970's (MODE C and mooring 542).

Frequency distribution for zonal and meridional contributions to K_E separately are contained in Figure 7. Note that the principal difference in the thermocline spectral shape is in K_u (Fig. 7a): K_v frequency distributions there are nearly the same (Fig. 7b). At abyssal depth, K_u and K_v (Figs. 7c and 7d) both have comparatively more energy at secular scale (they are "more red," or less peaked at the mesoscale) for 8298 relative to MODE C (4000). K_E in the eddy frequency band (Table 4) is higher for 829 relative to

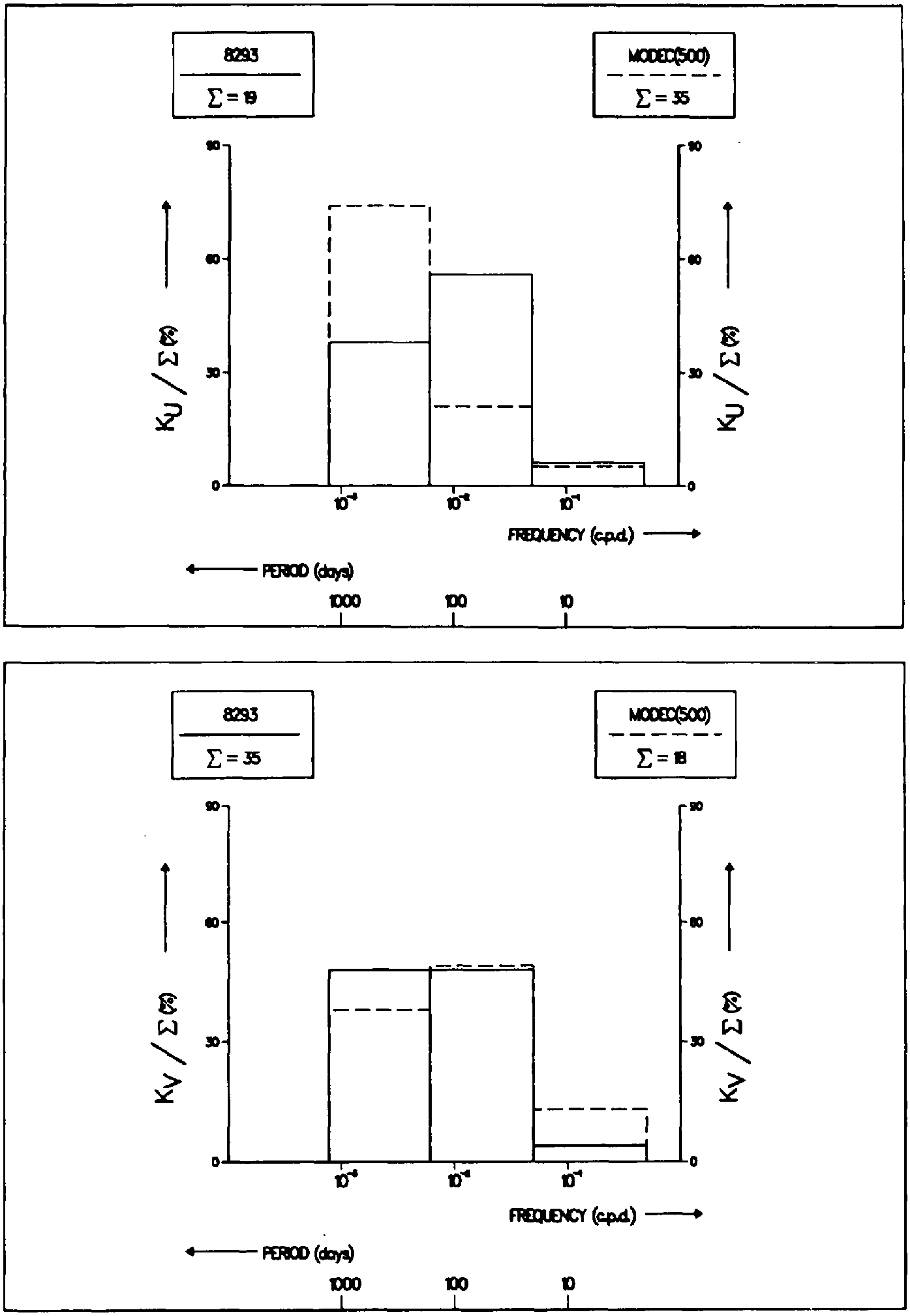
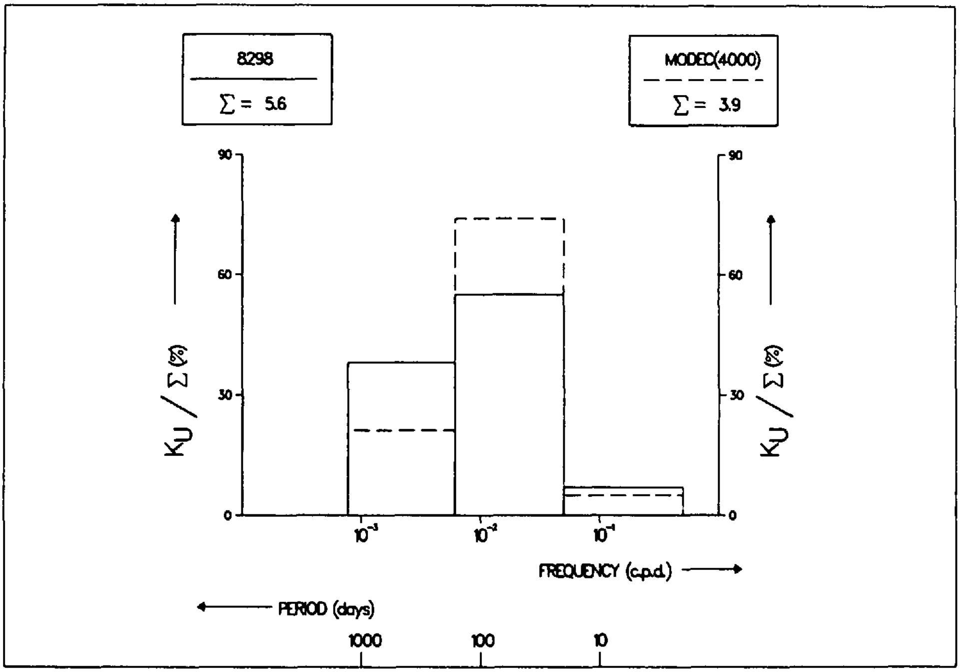


Figure 7. Normalized frequency distributions for the zonal (K_u) and meridional (K_v) kinetic energies at the key depths for MODE C and mooring 829.



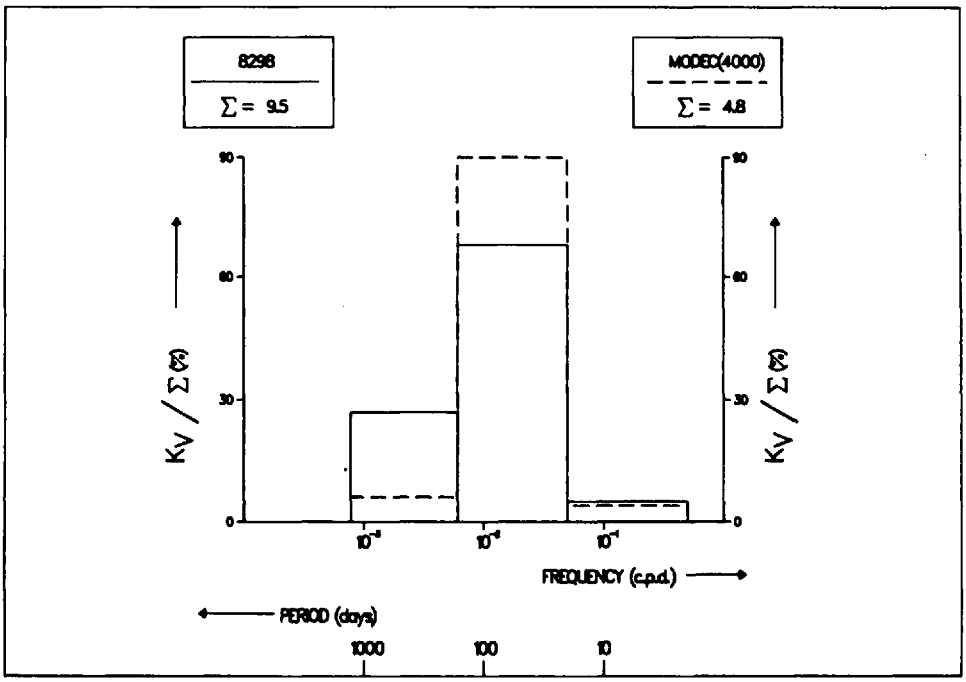


Figure 7. (Continued)

Table 4. MODE Area spectral partitioning.

	K_u (cm^2 s^{-2})			K_v (cm^2 s^{-2})			K_E (cm^2 s^{-2})		
File	Secular	Eddy	HF	Secular	Eddy	HF	Secular	Eddy	HF
8291	12.9	26.3	8.1	26.6	34.8	7.8	39.6	61.1	15.9
8293	7.0	10.3	1.2	16.8	16.6	1.3	23.8	27.0	2.5
8294	7.5	9.1	1.0	14.2	13.5	1.3	21.7	22.6	2.3
8296	2.1	2.9	0.4	1.6	5.8	0.4	3.7	8.7	0.9
8298	2.1	3.1	0.4	2.6	6.4	0.5	4.6	9.5	0.9
MODE C (500)	25.9	7.3	1.6	6.7	8.7	2.2	34.0	14.6	3.8
(4000)	0.8	2.9	0.2	0.3	4.3	0.2	1.2	7.2	0.4
5421	24.3	13.5	1.8	17.3	3.6	0.3	41.6	17.1	2.1
5424	2.4	1.5	0.1	0.1	4.6	0.1	2.5	6.1	0.2
5427	0.8	3.1	0.2	0.4	4.9	0.2	1.1	8.0	0.4

MODE C or 542 at all depths, primarily due to K_v. K_E (829) is generally larger than K_E (MODE C) in all frequency bands at abyssal depths (Table 4). The major differences in abyssal K_E are concentrated in K_v, which for 8298 at secular scale is an order of magnitude larger than for MODE C (4000). In the thermocline K_E (8293) is smaller than MODE C (500) for secular scales and larger for eddy scales; the two roughly balance. The major differences in K_u for the thermocline (Table 4) are confined to secular scale. As a result, the secular scale ratio K_u/K_v for 8293 (0.5) is about an order of magnitude smaller than for MODE C (3.8).

$\overline{u'v'}$ in the thermocline and above is also substantially different from decade to decade (Fig. 8), of roughly equal amplitude but opposite sign. The zonal mean flow component in the thermocline for 829 is of comparable amplitude and the same sign as the "historical" or MODE C values (Fig. 9), more so than one of the MODE C moorings itself (542), a result that might not have been anticipated. However, the meridional mean flows for 829 in the thermocline are more like 542 than MODE C. At 8298, $\bar{v}$ at 4000 m is an order of magnitude larger (Fig. 9) than observed for MODE C (4000). This is the major difference in time-averaged flow between the 1970's and 1980's at the MODE site. In the 1970's, some effort was also expended at a position about 100 km east of MODE Center (MODE Group, 1978) on the foot of the Bermuda Rise (at a location called MODE EAST), where a pronounced southerly mean abyssal flow was measured. At 4000 m on 829, the very large and negative $\bar{v}$ (Fig. 9) is more like that observed at MODE EAST (Schmitz, 1976b) than MODE C, again possibly due to a relatively minor horizontal shift or meander of a larger horizontal scale pattern. The resulting change in abyssal level mean kinetic energy between the 1970's and 80's was the largest relative difference found for any observable, a factor of 85.

Although the focus of this investigation is on MODE Center, there are somewhat similar observations available from a few other sites. The eastern North Atlantic

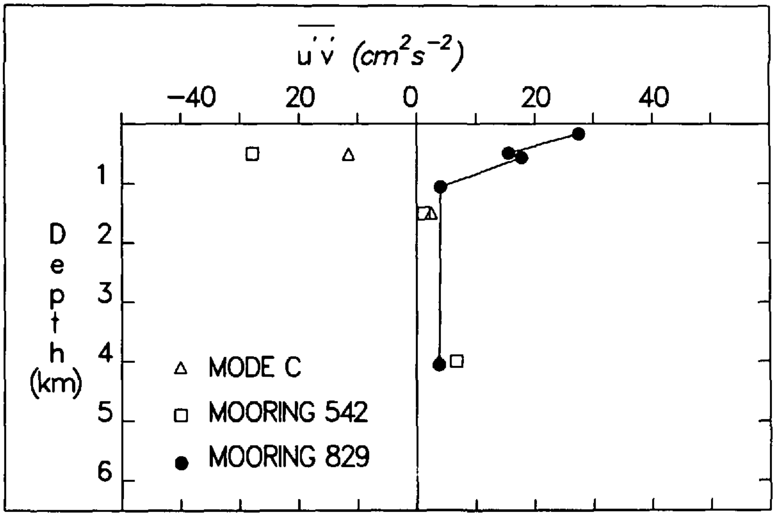


Figure 8. $\overline{u'v'}$ as a function of depth for the data sets under discussion.

results of Schmitz *et al.* (1988) and Zenk and Müller (1988) have already been mentioned. A mooring site near 30N, 147E with current meters at abyssal depths has been maintained for several years (Imawaki, 1985; Imawaki and Takano, 1982; Imawaki *et al.*, 1984), yielding data of great interest. This location is in a somewhat analogous area of the North Pacific relative to MODE. Dr. Imawaki has informed me by recent personal communication that he too observes energetic secular scale variability. Specifically, four separate 500-day estimates of $\overline{u'^2}$ vary from 4 to 16 $cm^2 s^{-2}$ and for $\overline{v'^2}$ from 6 to 10, similar to what we observe at 829 vs. MODE C. At the southern edge of the Gulf Stream System, near 344 and 70W (Site L), Briscoe and Weller (1984; see also Tarbell *et al.*, 1984, 1985) have acquired an interesting two-year (nominal) series (moorings 766 and 788). Figures 10 and 11 summarize the year-to-year variation of the vertical distribution of K_E and of abyssal spectra for these data. Changes in K_E (over a much shorter but still interannual time scale) at abyssal depths for Site L are roughly the same percentage-wise as for 829 vs. MODE C (Fig. 10), whereas the Site L abyssal spectra do not change notably in shape (Fig. 11).

Although the emphasis has been on temporal variability in time averages at interior ocean locations, as typified by MODE, there are general qualitative similarities that should not be forgotten. K_E estimates at the upper levels of mooring 830 (long-term abyssal data were not obtained) are comparable to those observed at 829 (Fig. 12), and spectra at similar depths are also not dramatically different. K_E for MODE C, to some extent mooring 829, and from moorings at the same latitude in the North Pacific are similar in general vertical structure (Fig. 13: mooring numbers 704 and 718 are from 28N in the western (152E) North Pacific).

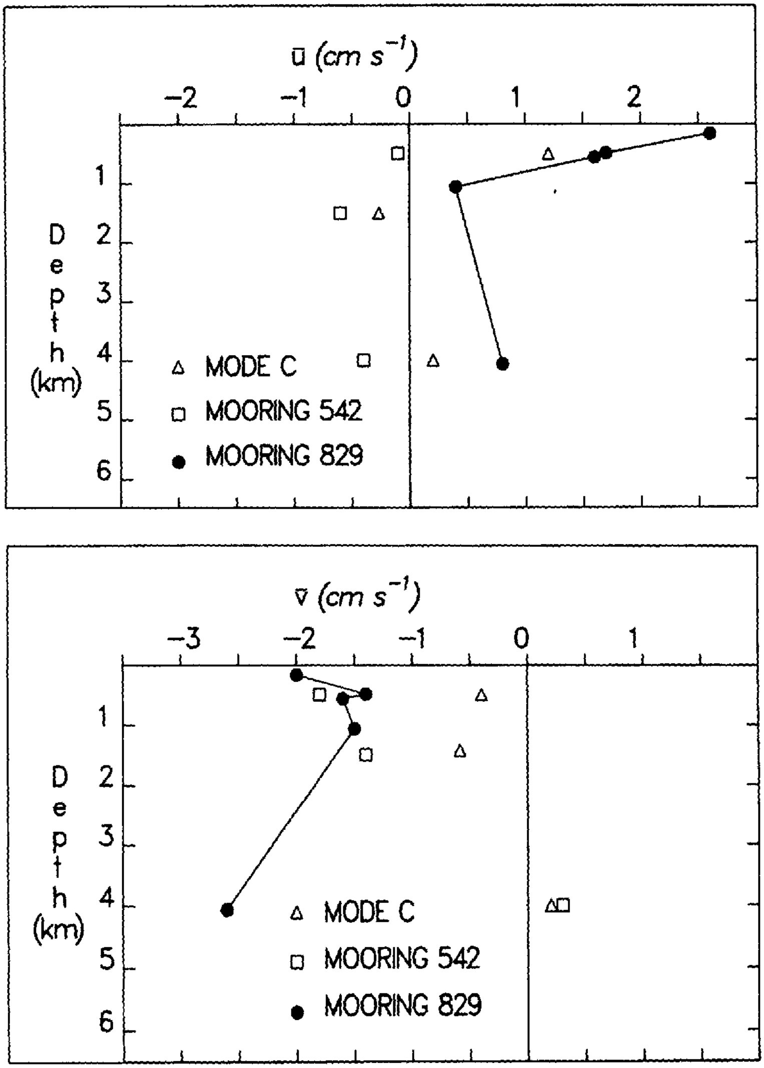


Figure 9. A mean flow intercomparison between 829, 542, and MODE C, as a function of depth: (a) zonal mean flow ($\bar{u}$), (b) meridional mean flow ($\bar{v}$).

4. Conclusions

A 20-month duration mooring from MODE Center (28N, 70W) in the mid-1980's exhibited notably different time averages relative to analogous observations from the mid-1970's, although there are also similarities of course. Specifically, abyssal kinetic energy levels are 50% larger in the 1980's, primarily due to an increase in meridional variance for the mesoscale eddy frequency band. In terms of total kinetic energy (mean + eddy) the change at 4000 m was about 100%. Spectral shapes also change,

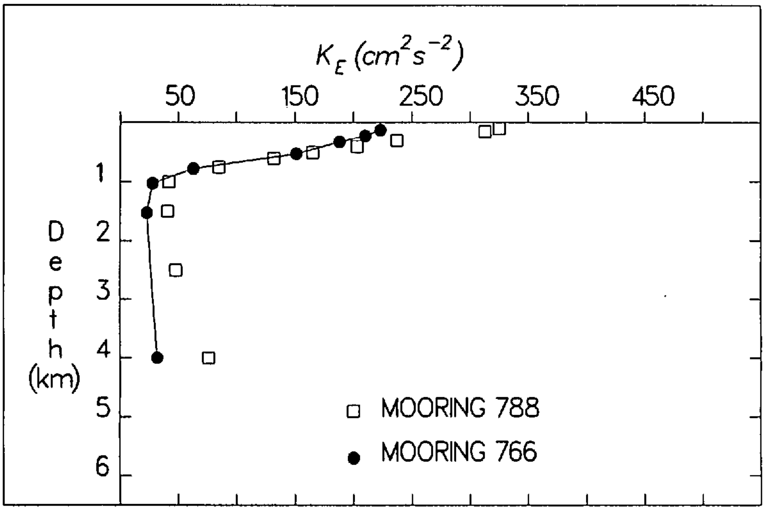


Figure 10. Year-to-year variation (data from mooring 766 intercompared with 788) of K_E as a function of depth at Site L (34N, 70W).

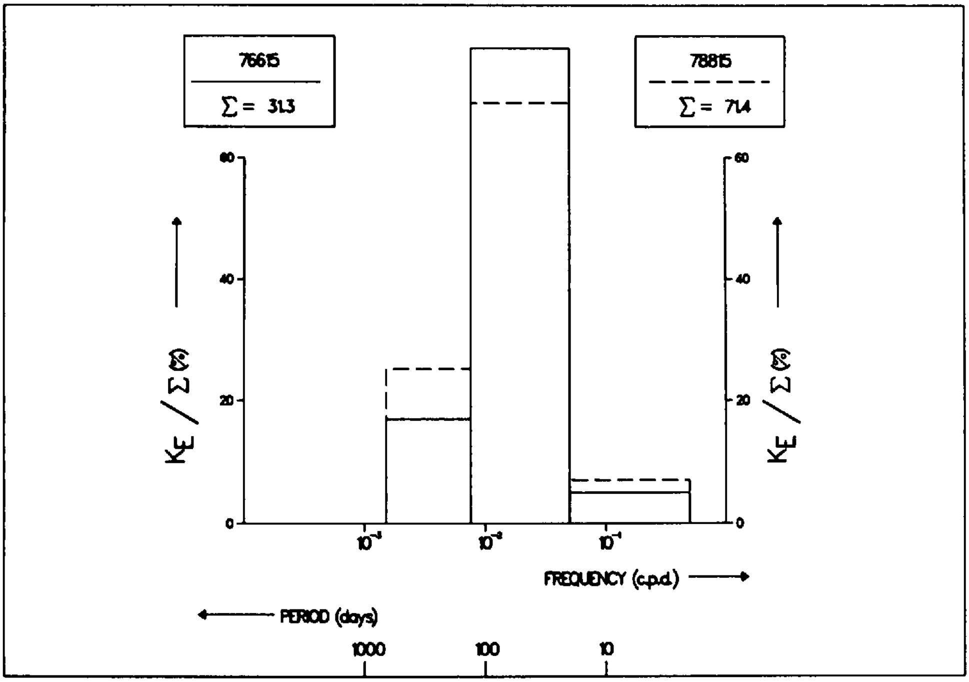


Figure 11. Year-to-year changes (intercomparing moorings 766 and 788 at 4000 m nominal, the 15 suffix) in the shape of the abyssal frequency distribution of K_E at Site L (34N, 70W).

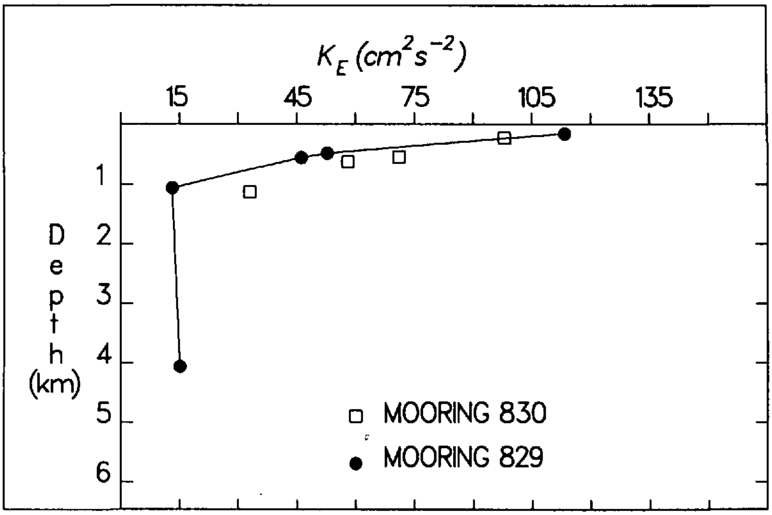


Figure 12. The vertical structure of K_E for moorings 829 and 830.

and the partitioning between zonal and meridional variances is different. In the thermocline in the 1980's $\overline{v'^2}$ is roughly twice $\overline{u'^2}$, whereas in the 1970's $\overline{u'^2}$ was roughly twice $\overline{v'^2}$ (MODE Group, 1978). This reverse of directionality in the thermocline applies to the interannual frequency band as well as total K_E. A "small" meridional displacement of the subtropical front or K_E pattern might rationalize the differences in

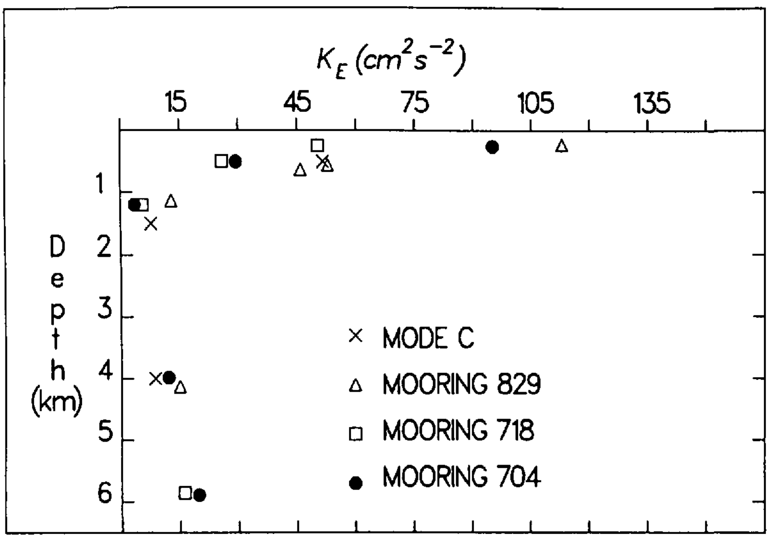


Figure 13. The vertical structure of K_E at MODE Center (28N, 70W) compared to a site (moorings 704 and 718) at 28N, in the western North Pacific (152E).

abyssal K_E and/or thermocline directionality. $\overline{u'v'}$ distributions in the thermocline are of equal amplitude but opposite sign. $\bar{v}$ increases dramatically at abyssal depths, being 2.6 cm s^{-1} to the south in the 1980's as opposed to 0.2 in the 1970's; overall there was a two order-of-magnitude change in the kinetic energy of the mean abyssal flow.

In summary, the MODE Area is neither quantitatively representative of the rest of the ocean nor are the MODE results of the 1970's quantitatively representative of measurements there ten years later. There is however, some general resemblance between measurements at 28N in the western North Pacific and Atlantic. The observation of strong interannual variability at these latitudes but east of the Mid-Atlantic Ridge has also recently been documented by Owens *et al.* (1988), Schmitz *et al.* (1988) and Zenk and Müller (1988). There is, in addition, evidence for factor of 50% or so variation on secular time scales at abyssal depths in the interior or low energy part (analogous to MODE) of the western North Pacific (Imawaki, personal communication).

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