Deep-Sea Research, Vol. 35, No. 8, pp. 1259–1268, 1988.
Printed in Great Britain.
0198–0149/88 $3.00 + 0.00

RAPID RESPONSE PAPER

Seven-year current meter record in the eastern North Atlantic

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(*Received* 20 *November* 1987; *in revised form* 3 *May* 1988; *accepted* 24 *May* 1988)

Abstract—Continuous current measurements at the 1000 m level were obtained in the central Canary Basin of the northeast Atlantic near 33°N, 22°W for 2398 days. Even with this very long time series no statistically significant mean current could be estimated at that level, because the energetic fluctuations are large compared to the weak mean. In the eddy scale range, i.e. at current fluctuations with scales between 47 and 455 days, a pronounced anisotropy between zonal and meridional components is apparent. For the first time in the subtropical North Atlantic gyre our data allow confirmation of the expected spectral decrease beyond the eddy scale peak in an eastern basin. With respect to future global experiments we wonder if our results from an eastern basin location are representative for the general circulation at mid-ocean sites?

INTRODUCTION

BEARING in mind the large spatial and temporal ranges of ocean currents, long-term direct current measurements are needed to observe the low-frequency motions associated with the gyre scale circulation. Especially in the mid-ocean, where eddies dominate the kinetic energy cascade (ROBINSON, 1983), a "mean" circulation scheme usually is masked by mesoscale fluctuations.

In recent years several groups have maintained efforts to continue long time series of current vectors at open ocean positions (DICKSON *et al.*, 1986; IMAWAKI and TAKANO, 1982; AAGAARD, personal communication). One such program was initiated in the central Canary Basin, northeast Atlantic, by Kiel University. Mooring NEADS 1 at 33°N, 22°W was part of the European North East Atlantic Dynamics Studies in which institutions from France, Germany and the United Kingdom cooperated (DICKSON *et al.*, 1985). After a short interruption in 1979 this position—later on called KIEL 276—was occupied by moored instruments continuously since April 1980. At 1000 m depth, i.e. in the Mediterranean water tongue, we have obtained the most complete record, consisting of eight independent mooring periods separated by service intervals of less than 48 h each. It is this subsample of the resulting time series that we present here.

The water depth at KIEL 276 is 5300 m. Within several tens of kilometers the bottom is extremely flat. Hydrographically the mooring position is situated at the northeastern rim of the subtropical gyre as seen in the σ_θ-distribution at 400 m depth (Fig. 1). The

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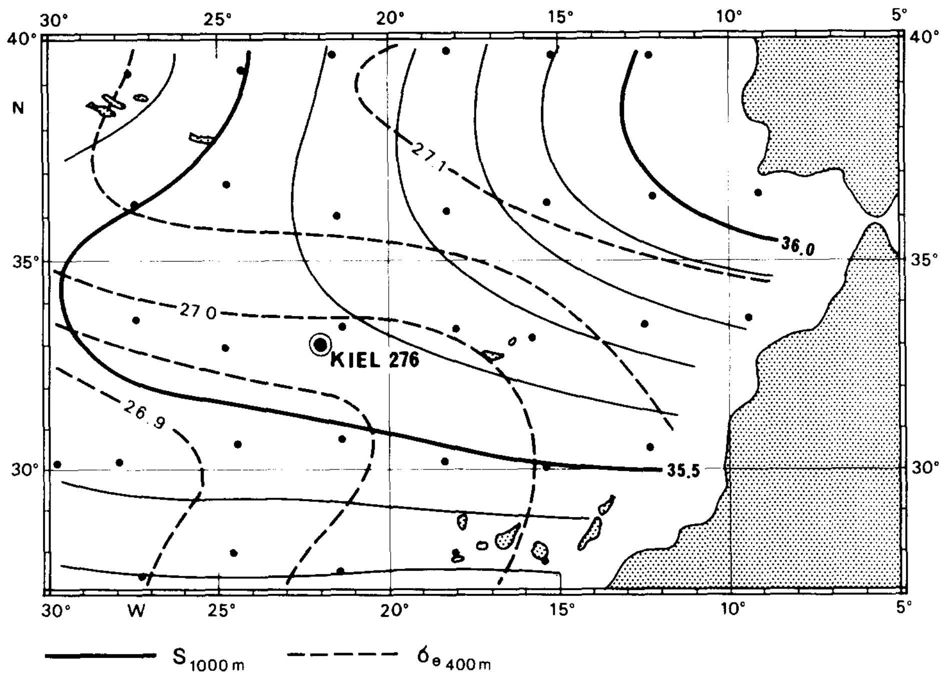

Fig. 1. Position and hydrographic environment of mooring site KIEL 276, water depth 5300 m. Hydrographic conditions of the upper water column at this typical oceanic station are marked by a pronounced main thermocline as part of the North Atlantic recirculation [σ_θ (kg m^{-3}) in 400 m] and by the Mediterranean Water tongue (salinity in 1000 m). Map was derived from a historical data base (WILLENBRINK, 1982), spatially averaged on 3° boxes (dots). At the mooring position the recirculation pattern and the Mediterranean Water spreading indicate sheared and prevailing zonal directions.

Azores Current is the dominant current feature in the thermocline circulation of this region (KÄSE and SIEDLER, 1982). On average this current system lies north of KIEL 276 (STRAMMA, 1984; KÄSE *et al.*, 1985). However, occasionally the mooring encounters extensions of the Azores Current, causing large velocity events in the current records (SIEDLER *et al.*, 1985). Below the main thermocline a smaller vertical temperature gradient coincides with the salty tongue of Mediterranean Water originating from the Gulf of Cadiz (Fig. 1).

METHODS AND RESULTS

Data have been collected from a conventional intermediate mooring with its uppermost buoyancy element at a nominal depth of 200 m. The mooring string is instrumented by seven Bergen current meters at nominal depths between 250 and 4900 m. Technical reports on annual segments of the long time series contain operational details and parts of simultaneous hydrographic data from the mooring site (MÜLLER, 1981, 1984; MÜLLER and ZENK, 1983; MÜLLER *et al.*, 1987; SIEDLER *et al.*, 1987).

From the level of the Mediterranean outflow, eight records of current speed and direction from depths between 935 and 1165 m at a sampling interval of 1 h and of up to one year length are available. In order to investigate low frequency motions on scales longer than 2 days, first a low pass filter with half power amplitude at 33 h was applied to each record removing tidal (DICK and SIEDLER, 1985) and inertial oscillations. Afterwards daily means from each record were calculated. The resulting time series are at varying depths and have gaps of order 1 week due to exchanges of moorings and filtering.

An interpolation scheme both vertically and in time domain had to be applied. The total data set KIEL 276 can be approximated by a modal decomposition (MÜLLER, 1987).

$$u_k(t, z) = \sum_{m=0}^{2} a_{km}(t) \cdot F_m(z) + \text{noise}.$$

Here $k = 1$ and $k = 2$ denote the east and the north component, and the $F_m(z)$ are the barotropic ($m = 0$) and the first two baroclinic ($m = 1,2$) normal modes. They can be derived as quasi continuous functions from the vertical structure equation for linear subinertial frequency motion in flat bottom oceans at mid-latitudes (e.g. PEDLOSKY, 1979) and from the mean stratification at the mooring site (SIEDLER and STRAMMA, 1983). The *a priori* unknown modal amplitude time series $a_{km}(t)$ were calculated for each time step

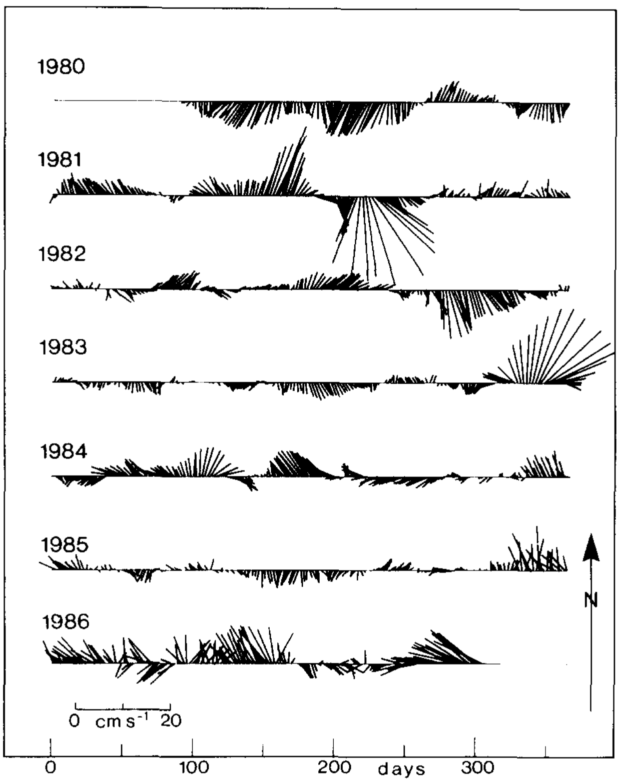

Fig. 2. Current vectors subsampled every 2 days at the 1000 m level of mooring KIEL 276, central Canary Basin. The data base consists of low pass filtered daily mean values (cut-off period 33 h), originally collected in hourly intervals. Vectors show distinctive background motion, interrupted by numerous single events, both with variable directions. Attempts have been made to interpret current bursts of mesoscale Mediterranean Water lenses interacting with the Azores Current system (KÄSE *et al.*, 1983, 1986; SIEDLER *et al.*, 1985; KÄSE and ZENK, 1987).

Table 1. Variability of main statistical parameters of current vectors in the central Canary Basin at 1000 m *depth on a 365 day basis. Note the large ranges of "mean" currents and the fluctuative energy which both exceed ratios of* 1:3. *FKE is fluctuative kinetic energy or vector variance. Components positive to east–north direction*

		1980/81	1981/82	1982/83	1983/84	1984/85	1985/86
Zonal							
Mean	(cm s^{-1})	−0.87	1.21	1.35	−0.24	−1.11	−1.02
Variance	(cm^2 s^{-2})	2.33	7.12	1.53	8.98	4.80	4.43
Meridional							
Mean	(cm s^{-1})	−1.56	0.17	−0.86	0.44	0.87	0.67
Variance	(cm^2 s^{-2})	10.75	24.66	7.55	11.54	5.39	8.19
Vector variance FKE	(cm^2 s^{-2})	6.54	15.89	4.54	10.26	5.10	6.31

using a linear least-square minimization procedure fitting the vertical distribution of both observed velocity components. In a further step vertically interpolated time series of both velocity components at 100 m were obtained. Remaining gaps in time were closed by local spline interpolation (STURGES, 1983), resulting in a total record length of 2398 days.

In Fig. 2 we present the Eulerian vector time series of ocean currents at KIEL 276 from 1980 to 1986 in 1000 m depth. The yearly records are dominated by events that appear in irregular intervals. No obvious periodicity can be detected. The year-to-year variability is notably dramatic as Table 1 shows in detail. The record indicates that 1981/82 were the most and 1985/86 the least energetic years within the mesoscale (eddy) band. Fluctuations are discussed in the following sections.

STATISTICS

Although the record obviously is not normally distributed we calculate record means as first estimates of the corresponding moments of the underlying process (Table 2). Error estimates are derived from the estimated moments, the record length, and the time scales

Table 2. Statistics of Eulerian current measurements in the Canary Basin, mooring site KIEL 276, 33°N, 22°W, *at the* 1000 m *depth level. Record length of low pass filtered daily means after interpolation is* 2398 days. *Errors and error ranges give the* 95% *confidence limits assuming normal distribution of a stationary process and time scales computed as integrals of the autocorrelation function to its first zero crossing. The eddy flux is not significantly different from zero. Components positive to east–north direction. Vector variance denotes the fluctuative part of kinetic energy (FKE). For more details see text and MÜLLER* (1987)

	Zonal	Meridional	Vector
Mean flow (cm s^{-1})	−0.30 ± 0.79	0.15 ± 0.61	0.34
Direction (°TC)			296
Stability			0.06
Time scale (days)	53	19	
Degrees of freedom	45	126	
Mean kinetic energy (cm^2 s^{-2})	0.05	0.01	0.06
Variance (cm^2 s^{-2})	7.0	12.4	9.7
Error bounds of variance (cm^2 s^{-2})	4.8, 11.1	10.0, 16.6	
Eddy flux (cm^2 s^{-2})			0.63
Eddy flux direction (°TC)			6

of both current components on the 95% confidence level. Here the time scale has been calculated as the integral of the corresponding autocorrelation function until its first zero-crossing. This method has been used by LUYTEN (1982) and gives comparable values to those from the deep sea in the same region (DICKSON *et al.*, 1985). The mean current is weak (−0.30 cm s^{-1} for the eastward, +0.15 cm s^{-1} for the northward component) and not significantly different from zero. Notable is the much longer time scale of the zonal component (53 days) as compared with that of the meridional component (19 days). Similar results were found in the MODE region in the main thermocline of the central northwest Atlantic (RICHMAN *et al.*, 1977) and may indicate an increase of the kinetic energy at low frequencies in the zonal component as expected from linear baroclinic Rossby wave theory, although the total variance in the meridional component (12.4 cm^2 s^{-2}) clearly dominates that of the zonal component (7.0 cm^2 s^{-2}).

The covariance of current components ($\overline{u'v'}$ = 0.63 cm^2 s^{-2}) is not significantly different from zero and so is the eddy momentum flux direction. The directional stability, defined as the ratio of mean vector to mean scalar speed (DICKSON *et al.*, 1985), can vary between 1 and 0, representing either a constrained flow with no directional variations or a random directionality. Even after nearly 7 years record length its value (0.06) is extremely low and several times even approaches zero.

From this purely statistical analysis one might conclude that the Mediterranean outflow at a distance of approximately 1500 km from its source is more diffusive than advective. However, since the recent detection of submesoscale vortices (MCWILLIAMS, 1985) embedded in the Mediterranean Water tongue (cf. ARMI and ZENK, 1984), this simple spreading model, though supported by our current meter observations, requires a basic revision. Such vortices advect a non-negligible part of high salinity water westward and southward and distribute salt on their way while decaying by diffusion.

SPECTRAL ESTIMATES

Frequency spectra of the meridional and zonal components and kinetic energy per unit mass have been calculated as an averaged spectrum from two pieces of the record, each 2048 days long and shifted by 349 days in order to utilize the full record length. Furthermore the resulting averaged spectra were divided into six averaged frequency bands (Table 3) and are displayed in energy preserving form (SCHMITZ, 1978), i.e. areas below the curve represent energy contents in the corresponding frequency range (Fig. 3a). For comparison a log–log representation is also shown (Fig. 3b).

In the notation of WUNSCH (1981) the submesoscale bands represent the isotropic frequency range where one often finds the same energy level and decay of the spectrum

Table 3. *Period (frequency) bands used for spectral analysis in Fig. 3 together with degrees of freedom (DOF)*

No.	Periods (days)	DOF	Bands
1	2.0 – 7.0	1490	Submesoscale, isotropic
2	7.0 – 14.5	272	
3	14.5 – 46.5	196	
4	46.5 – 180	70	Mesoscale, eddy scale
5	180 – 455	12	Annual
6	455 – 4096	8	Transannual

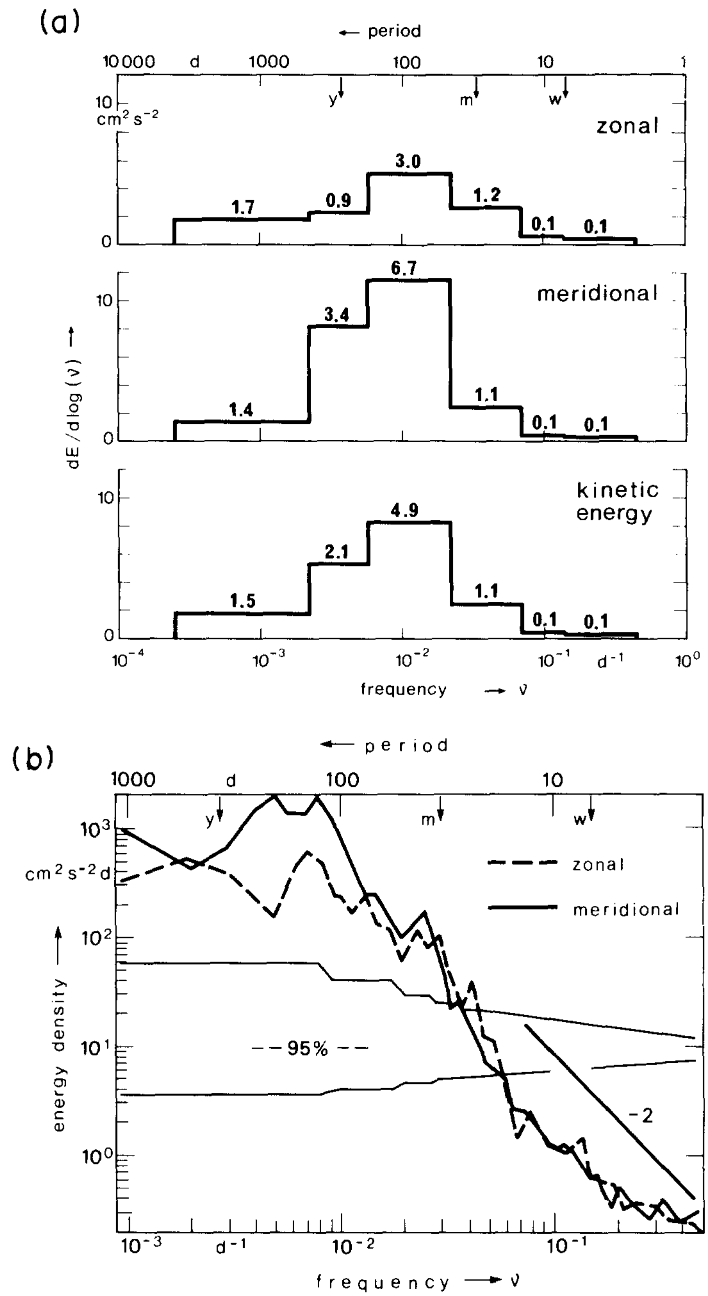

Fig. 3. Spectral estimates of the long-term current vector record at mooring site KIEL 276, 1000 m level. On the upper axes yearly (y), monthly (m) and weekly (w) periods are labeled. The variance-preserving form (a) has been divided into zonal (top) and meridional components (middle). The third spectrum (bottom) represents the total energy. Numbers indicate energy contents in frequency bands according to Table 3. All three spectra are dominated by a peak in the mesoscale (eddy) range, 0 (month). Zonal and meridional components indicate a significant difference in energy levels, the meridional mesoscale band being at least two times more energetic than the zonal band. This spectral energy distribution in the eastern North Atlantic appears to be of universal importance for open ocean stations as comparisons with similar low-frequency spectra at mid-depth in the western North Atlantic (SCHMITZ, 1978; OWENS *et al.*, 1988) and the western North Pacific (IMAWAKI and TAKANO, 1982) show. In the log–log form (b) the mesoscale band appears less pronounced. However, it contains spectral slopes, representative for various bands. This spectrum was calculated from three detrended overlapping pieces of 1024 days length each.

towards higher frequencies (–2 in a log–log representation) for both components (WUNSCH, 1981). The spectrum of KIEL 276 makes no exception. In the mesoscale band the meridional component clearly dominates by a factor of more than two in contrast to spectra from the POLYMODE clusters A and B in the northwestern Atlantic (WUNSCH, 1983) where the spectra are still isotropic down to 10^{-2} d^{-1}. The reason is not yet clear, but may be associated with instability processes (KÄSE and SIEDLER, 1982; SIEDLER *et al.*, 1985).

The dominance of the meridional component is even stronger in the annual band, although on a lower level. No annual periodicity could be detected in this band up to now (MÜLLER, 1987), and thus we may regard this part of the spectrum as continuation of the mesoscale band at lower frequencies. In earlier studies dealing with shorter time series from the northeastern Atlantic, this band could not be resolved from the pure mesoscale. Therefore those spectra were red (see DICKSON, 1983; DICKSON *et al.*, 1985). Here we are able to show the energy decay toward lower frequencies. The transannual or secular band in the SCHMITZ (1978) nomenclature contains slightly more energy in the zonal component compared with the meridional. Although certainly not yet significant on a high confidence limit, such a behavior of the spectrum confirms results from baroclinic Rossby wave theory. When a linear trend is removed from the time series before calculating the spectra, only the energy content in the transannual band of the zonal component decreases drastically from 1.7 down to 1.0 cm^2 s^{-2} and thus clearly below the level for the meridional component which drops only marginally from 1.4 to 1.3 cm^2 s^{-2}. This again hints of zonalization of the spectrum at very low frequencies.

LONG-TERM CHANGES

In order to describe some prominent characteristics of the year-to-year variability in Fig. 4, we present a progressive vector diagram of the time series shown in Fig. 2, together with information from concurrent oceanographic experiments in the same area.

The first year, 1980, appears to be rather atypical. For more than 6 months a southerly flow was interrupted only by a short-term counterflow in the autumn. In the following year the mooring site was hit by a highly saline lens of Mediterranean Water. As ARMI and ZENK (1984) showed, these anticyclonic vortices (Fig. 4a) can cause local speed and temperature maxima. the "mean" currents at KIEL 276 pointed towards the African shelf until autumn 1983. Another interesting detail of this time series was utilized to interpret a mesoscale hydrographic survey in April 1982. The warm feature B migrated (Fig. 4b) northeastward in accordance with the general trend of the shown progressive vector diagram (KÄSE and ZENK, 1987).

In autumn 1983 a notably dramatic change occurred in the current record. Near the (present) end of our series, currents showed a prevailing westward direction, again interrupted by strong current events, i.e. November 1984. Minimal currents appeared in 1984. In this year a combined German/United States survey (KÄSE *et al.*, 1986) investigated the mesoscale area south of the Azores again, where the subsurface float EB 139 was launched (Fig. 4c). Identical current directions in the float trajectory (1140 m concurrent depth) and the vector diagram were detected as the float passed the location KIEL 276 (PRICE *et al.*, 1986).

In a first analysis of their float data, SCHMITZ *et al.* (1987) describe a westward (32°N) "jet" of Mediterranean Water located approximately 100 km south of KIEL 276 during 1984. It is tempting to interpret the stable current direction found at the end of our

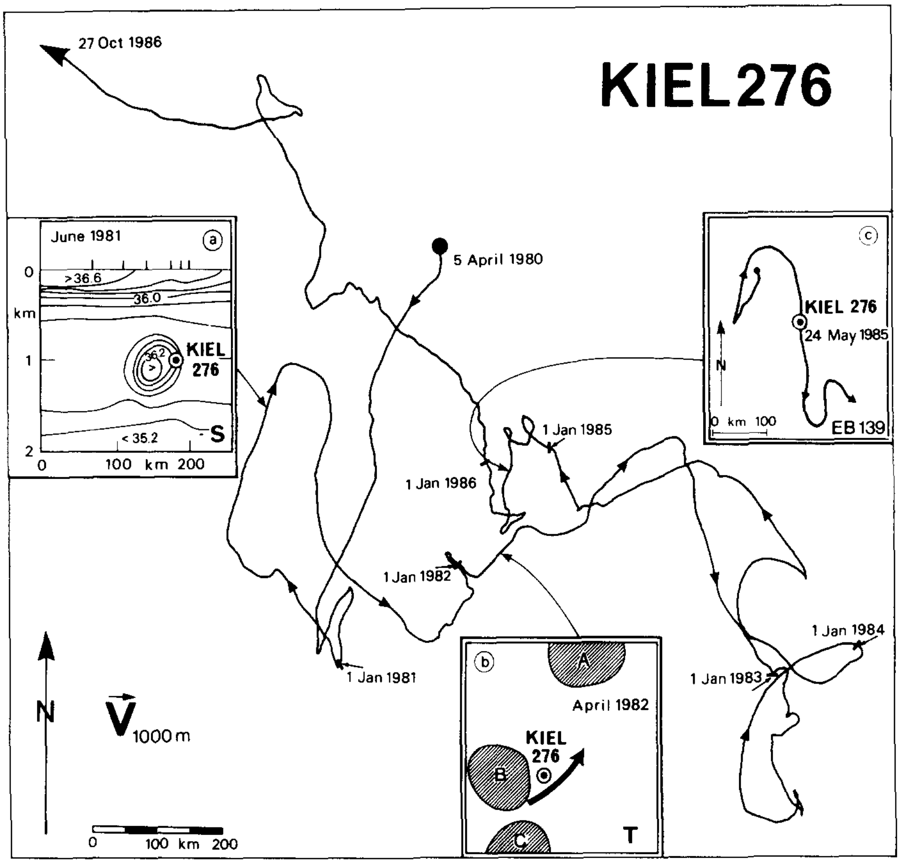

Fig. 4. Progressive vector diagram from the nearly 7-year current record at KIEL 276, 1000 m, central Canary Basin. In this display, individual current vectors as seen in Fig. 2, were coupled in a long series starting in April 1980, ending in October 1986. Note the interannual variability. Until 1983 a "mean" current towards the east was observed which reversed since then. Inserts a–c represent synoptic scenes which have been described elsewhere in the literature (ARMI and ZENK, 1984; KÄSE and ZENK, 1987; PRICE *et al.*, 1986).

record, summer and autumn 1985, as the same westward flow shifted to the location of KIEL 276 (33°N).

CONCLUSIONS

Mooring site KIEL 276 is typical for the Mediterrranean Water level in the Canary Basin and away from any intensive boundary currents. However, this dynamical mode irregularly is replaced by periods of moderately strong currents associated with transitions of the Azores front or of isolated lenses of Mediterranean Water. They cause abrupt change in mean directions and prevent us from calculating a statistically significant averaged flow vector even after 7 years of observations. It is far from clear whether this result is typical for mid-ocean mid-depth records; KIEL 276 with its proximity to the Azores front may be an exceptional site. On the other hand it would be unwise to assume *a priori* more stable conditions at positions far from strong currents.

Mooring location KIEL 276, half-way between the Azores and the Canary Archipelago, was chosen originally because of its convenient position for operations from Germany. It was hoped that current measurements there might be representative of general, mid-ocean conditions. A view of the spectral energy partition (Fig. 3) in comparison with similar investigations from other open ocean locations shows that the significantly different levels in the mesoscale zonal and meridional components, indeed, appear to be of general importance. The observed eddy statistics are reminiscent of other Eulerian observations in deep western basins of the North Atlantic (SCHMITZ, 1978) and the North Pacific (IMAWAKI and TAKANO, 1982). However, a Lagrangian spectrum from the western basin at the same depth level (OWENS *et al.*, 1988) does not confirm the shown asymmetry between the larger meridional and the lesser zonal kinetic energy so clearly. A reason for that fact remains to be determined.

We feel that our results are timely and relevant for the ongoing planning phase of the World Ocean Circulation Experiment (WOCE), both in respect to experimental plans and theoretical considerations. Due to the restricted observational time scale of WOCE, it appears to be advisable to run current meters at an open ocean site uninterrupted for several years and to combine their limited capabilities with other subtle methods like Lagrangian time series, satellite altimeter observations and tracer measurements.

Acknowledgements—This work has been supported by the Deutsche Forschungsgemeinschaft (SFB 133). A first draft was written while WZ enjoyed the hospitality of the Woods Hole Oceanographic Institution as a guest investigator. The manuscript was finished at Texas A&M University where TJM benefited from discussions with numerous colleagues. WHOI contribution no. 6758.

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