Long-term water movements in the southern trough of the Charlie-Gibbs Fracture Zone

by Robert R. Dickson,[1] Paul A. Gurbutt,[1] and Kenneth J. Medler[1]

ABSTRACT

The first long-term (250 d) current measurements from the southern trough of the Charlie-Gibbs Fracture Zone indicate persistent westward flow along the north wall and a steady eastward drift along the lower south wall. Net volume transport varies from westerly to easterly with a 2-3 month periodicity, but no seasonal cycle is evident. Overall, the separate westward and eastward transports are in balance.

Close to the valley walls, eddy kinetic energies are roughly equivalent to those of the mean flow, but exceed these by well over an order of magnitude at the upper levels on each mooring. In the central part of the valley the low frequency fluctuations are comparatively energetic for this depth layer in the North Atlantic and the vertical distribution of eddy kinetic energy is strongly frequency dependent, with k_E increasing upward for the longer time scales and intensifying toward the bottom at higher frequencies. These results are consistent with earlier observations from the northern trough of this Fracture Zone.

1. Introduction

It is now well established that the bulk of Norwegian Sea Deep Water overflowing the Iceland-Scotland Ridge eventually flows southward along the eastern flank of the Reykjanes Ridge. While the shallower part of this flow is able to cross the snout of the Reykjanes Ridge as its crestline deepens southward (Shor *et al.,* 1979), the Charlie-Gibbs Fracture Zone (CGFZ) at 52-53N offers the first westward passage for overflow water lying at depths greater than 2500 m. Since Cooper (1955) first suggested a deep transport of overflow water through the Mid Atlantic Ridge on the basis of high salinities found in the western basin, numerous investigators have described the morphology of the Fracture Zone and have made estimates or direct measurements of the flow passing through it.

The essential characteristics of the Fracture Zone itself are conveniently summarized by Harvey (1980). It comprises two transform valleys orientated at 095-275°, each with maximum depths exceeding 4500 m and with sill depths of

1. Ministry of Agriculture, Fisheries and Food, Directorate of Fisheries Research, Fisheries Laboratory, Lowestoft, England.

3600-3700 m. The sills occur at 35W in the northern valley and at 30W in the southern. These two zonal troughs are separated by a mid-fracture transform ridge with an irregular crestline which nonetheless appears to prevent communication between the troughs at depths greater than 3300 m (Harvey, 1980).

The deep transports through the Fracture Zone are also becoming better known, though elements of controversy certainly remain. Worthington and Volkmann (1965) first estimated the net transport at 4.6 Sv toward the west in April 1964, using short-term (~ 30 h) current meter and neutrally-buoyant float deployments to fix their geostrophic calculations. Later, from seismic reflection profiles of the sediments, Le Pichon *et al.* (1971) suggested that an eastward flow existed in the near-bottom layers of the northern trough, underlying the overflow water, but this suggestion was disputed by Worthington and Wright (1971) on the basis of hydrographic evidence. Shortly afterward Garner (1972) supplied limited supporting evidence for the existence of a westward flow in the deepest layers of both troughs. His 7-day records at 50 and 650 m above the bottom showed a mean westward drift of about 3 cm s^{-1} with a semi-diurnal tidal signal superimposed. It is relevant to add that these moorings were set in the deepest part of the southern trough (depth = 4390 m) and a little way up the north wall of the northern trench (depth = 3840 m). The first long-term current meter records from the Fracture Zone were obtained in June 1976 when R.V. *Knorr* of Woods Hole Oceanographic Institution recovered a 9-month deployment of three moorings from the northern trough. Once again these moorings were from the north-center and north wall of the trough and once again the eight current meters, set at depths ranging from 988 to 4277 m, indicated a net westward flow at all but the shallowest depth of measurement (Schmitz and Hogg, 1978). The time-averaged zonal flows of 3-4 cm s^{-1} westward for the deep instruments were in surprisingly good agreement with those found by Garner, bearing in mind the energetic low frequency fluctuations which Schmitz and Hogg describe from their long-term data. Shor *et al.* (1979) and Harvey and Shor (1978) make the additional step of calculating the westward volume transport of deep water from these data (~ 2.4 Sv below 2000 m depth), but Schmitz and Hogg evidently regard such calculations as inadvisable pointing out that "the data . . . were collected in the northern portion of the northern trough in CGFZ only and all conclusions should be restricted accordingly."

The interpretation of hydrographic data collected by R.V. *Knorr* in 1975 during the deployment of these moorings has also proved controversial. Finding deep water of western origin in the western part of the CGFZ, Shor *et al.* invoke as an explanation the possibility of eastward mean flow through the southern trough, leakage to the northern trough through a gap in the median ridge at 34°30′W, and subsequent westward entrainment. Schmitz and Hogg (1978) suggest that such an involved explanation is unnecessary, pointing out that the 200 km penetration of western basin water into the CGFZ corresponds approximately to the advective length scale of the deep eddies that they describe. But Harvey (1980) has examined a more extensive historical data set of 112 hydrostations from the NODC file in the area 51-54°N, 28-44°W. He concurs with Worthington and Wright (1971) that the available data show no net eastward movement of bottom water in the CGFZ east of the sill. Harvey and Shor (1978) are clearly not satisfied that the available data give a complete picture of events. In particular they note that a section across the northern trench at 35°30′W in June 1975 gives some indication that the surface of the cold dense (western basin) water slopes up toward the south and later (p. 5) submit that "the possibility of some of the cold dense water passing through to the eastern basin of the North Atlantic without being observed . . . should not perhaps be entirely discounted."

This continuing uncertainty concerning the presence or absence of easterly transport through the CGFZ is the natural result of a situation where the hydrocast coverage is sparse in relation to the complex topography and where all existing current meter records (both short- and long-term) have been confined to the central and northern parts of the troughs.[2] As Schmitz and Hogg (1978) correctly point out "Answers to many of the questions that have been raised concerning the pattern of the mean flow and the properties of the eddy field in CGFZ will require additional measurements in other areas such as the southern region of the northern trough, the southern trough, and also along the median ridge." The present report examines both these questions in describing the first long-term current meter records from the southern trough of the CGFZ, including the first records of flow from the south wall of either valley.

2. Method

The three current meter moorings in question were set by R.V. *Cirolana* on 22 and 25 October 1977 and were recovered on 2 July 1978. The bathymetry of the mooring site is illustrated in Figure 1 with mooring positions indicated by the three solid circles south of Hecate Bank; this chart, kindly provided by R. C. Searle, Institute of Oceanographic Sciences, Wormley, England, incorporates the results of a survey by R.R.S. *Discovery* in 1977 using GLORIA side-scan sonar (Searle, 1979) with minor modifications from data obtained by R.V. *Cirolana* in July 1978. Figure 1 also indicates the position of a detailed bathymetric transect of the valley along 30°59′W made during the latter cruise, and the positions of the three moorings are projected on to this transect in Figure 2. As shown, each mooring incorporates two current meters (Aanderaa RCM 4) which were set to an hourly sampling frequency. Five of the six meters yielded good quality data for the dura-

2. The sole exception is a 35 h record obtained in July 1975 from the base of the south wall in the northern valley. This record is described later.

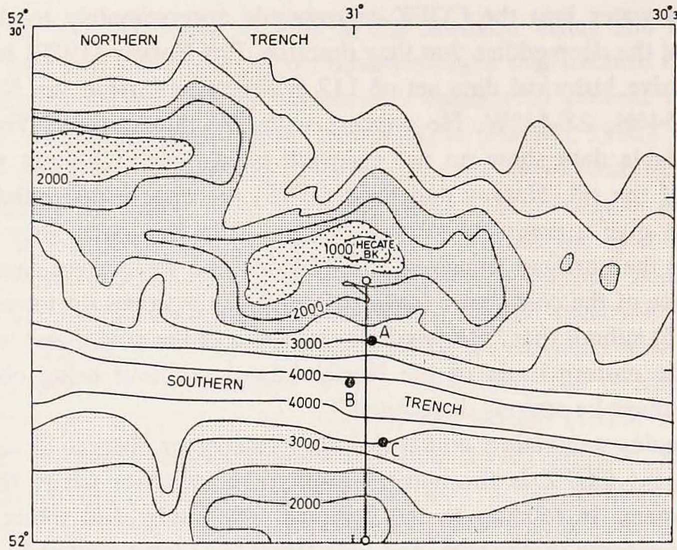

Figure 1. Bathymetry of the mooring site (m) in the southern trough of the Charlie-Gibbs Fracture Zone, south of Hecate Bank; chart from Searle (1979) with minor modifications by R.V. *Cirolana* in June 1978. Positions of moorings A, B and C are shown by solid circles and the location of a detailed bathymetric transect along 30°59′W is also indicated (• ——— •).

tion of the experiment while one gave a short record. Positions, meter depths and data duration are noted in Table 1.

3. Results

Basic time averages for the five long records are listed in Tables 2a and 2b with the upper and bottom instruments designated as $A_{(U)}$, $A_{(B)}$ etc. Table 2a is concerned with means and extremes of hourly values while Table 2b lists means of daily values obtained using a low-pass Gaussian filter similar to that described by

Table 1. Mooring details.

Mooring	Position	Water depth (m)	Instrument depth (m)	Date set	Date recovered	Record length (d)
A Upper	52°11.8′N 30°58.4′W	3050	2500	25 Oct 1977	2 Jul 1978	250
Bottom			3000			250
B Upper	52°09.4′N 31°00.2′W	4027	2977	22 Oct 1977	2 Jul 1978	253
Bottom			3977			253
C Upper	52°05.9′N 30°57.0′W	3577	3027	25 Oct 1977	2 Jul 1978	40
Bottom			3527			250

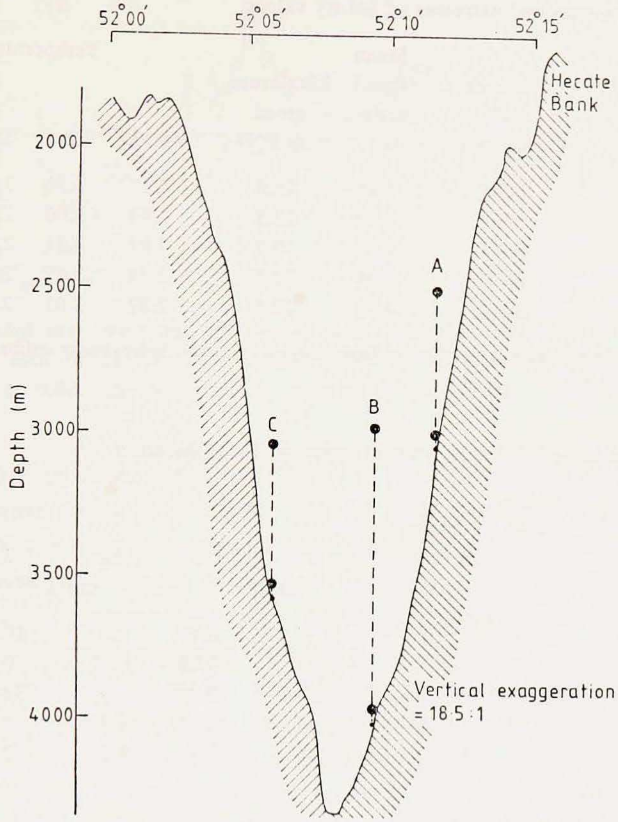

Figure 2. North-south bathymetric transect of the southern trough at 30°59′W with mooring positions and instrument depths superimposed.

Schmitz (1974) with a cut-off at 2 d. In the latter case, each filtered record was truncated at a common 247 d duration. Following Schmitz and Hogg (1978) the symbols used in Table 2b and in the remainder of this report ($\bar{u}$, $\bar{v}$, k_M, k_E) are defined as the time-mean east velocity component, time-mean north velocity component, kinetic energy per unit mass for the time-averaged flow and eddy kinetic energy per unit mass respectively. The "steadiness factor" quoted is the ratio of mean velocity to mean speed expressed as a percentage and provides a convenient indication of the directional stability (or otherwise) of the mean flow (see Neumann, 1968; Ramster, Hughes and Furnes, 1978).

4. Mean flow

Table 2b provides information on both the direction and the variability of the mean flow through the southern trough, west of its sill. Net westward flow was

Table 2a. Selected means and extremes of hourly values.

Record	Depth (m)	Number of observations	Mean speed (scalar) (cm s^{-1})	Maximum speed (cm s^{-1})	Temperature (°C) Mean*	Max.	Min.	S.D.	$\bar{\theta}$†
$A_{(U)}$	2500	6001	4.94	25.0	3.17	3.36	3.00	0.05	2.96
$A_{(B)}$	3000	6001	3.40	13.5	2.92	3.06	2.78	0.05	2.66
$B_{(U)}$	2977	6074	7.56	30.9	2.97	3.51	2.87	0.03	2.71
$B_{(B)}$	3977	6075	6.06	27.5	2.78	2.87	2.71	0.03	2.41
$C_{(B)}$	3527	6002	4.62	20.5	2.82	3.01	2.73	0.05	2.51

* Fenwal 2 *k* isocurve thermistor installed in high resolution mode, individually calibrated to ±0.01°C.
† Assumes salinity of 35‰.

Table 2b. Mean of low-passed daily values: common 247 d duration.

Record	Depth (m)	Mean speed (vector) (cm s^{-1})	Mean direction (°)	$\bar{u}$ (cm s^{-1})	$\bar{v}$ (cm s^{-1})	k_M (cm^2 s^{-2})	k_E (cm^2 s^{-2})	"Steadiness Factor" (%)
$A_{(U)}$	2500	0.57	36	0.34	0.46	0.2	10.7	14.9
$A_{(B)}$	3000	0.82	291	−0.77	0.29	0.3	0.4	72.6
$B_{(U)}$	2977	1.63	93	1.63	−0.09	1.3	34.0	23.5
$B_{(B)}$	3977	3.36	263	−3.33	−0.43	5.7	9.7	71.6
$C_{(B)}$	3527	2.71	101	2.66	−0.54	3.7	2.2	91.2

found in only two of the five long records ($A_{(B)}$ and $B_{(B)}$). These records are both from meters close to the bottom on the north wall of the trough where the strongest westward flow might be expected; the kinetic energy of the mean flow (k_M) differs by more than an order of magnitude between these two points with the stronger westward flow lying near the bottom of the north wall. Toward the foot of the south wall ($C_{(B)}$) the flow was intermediate in strength ($k_M = 3.7$ cm^2 s^{-2}) and consistently toward the east throughout the entire period of the record.

A second feature of Table 2 concerns the fact that the three near-bottom records ($A_{(B)}$, $B_{(B)}$ and $C_{(B)}$) were markedly steady in direction with steadiness factors of >70%, while the upper records ($A_{(U)}$, $B_{(U)}$ and also the 40 d record at $C_{(U)}$) were highly variable, with steadiness factors of 14.9, 23.5 and 19.1% respectively. The ratio k_E/k_M provides a different method of expressing the same observation. For the three bottom records the mean and eddy kinetic energies are roughly equivalent but for $A_{(U)}$, $B_{(U)}$ and $C_{(U)}$ the k_E:k_M ratios were 53:1, 26:1 and 32:1 respectively.

A combination of Table 2b above with Table 2 of Schmitz and Hogg would give flow statistics from five records in the deeper layers (> 2500 m) of each trench. Although these data sets are of comparable length (247-260 d) and seasonal cov-

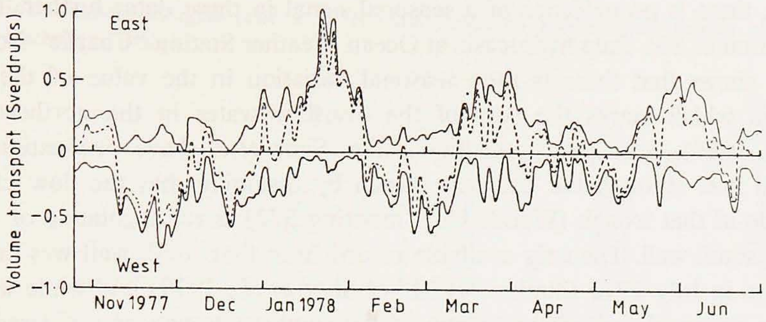

Figure 3. Estimated east, west and net (– – –) daily transport (Sv) through one-half of the cross-sectional area of the southern trough below 2000 m depth. This restricted cross-section is used to reflect the restricted coverage of the trench by the three moorings.

erage, they differ in date, depth and site (i.e. location relative to the the trench walls). Since mean flows in this area may be quite localized and since low frequency variability is both extreme and depth dependent it would seem inadvisable to compare ensemble averages of k_M and k_E for the two troughs in any detail, beyond the general statement—readily apparent from these tables—that kinetic energy levels are generally higher in the northern trough.

There is better justification for attempting to estimate the volume transport through the southern trough, since the three moorings under discussion do provide at least a partial coverage of the flow on both walls and in the center of this valley. The present array was in fact assumed to cover only one-half of the cross-sectional area of the valley below 2000 m depth (see Fig. 2) and each of the six records were assumed to be representative of the flow over one-sixth of that restricted cross-section. The mean daily zonal flows recorded at each instrument were then integrated to provide separate estimates of the total westward, eastward and net daily volume transport through that lower half of the section (Fig. 3). As shown the transport alternates between episodes of net westward and net eastward flow, with a periodicity of some 2-3 months. Overall, the westward and eastward transports for this "half section" are in almost perfect balance with means of 0.231 and 0.245 Sv respectively, though of course this does not necessarily imply zero transport through the section since these twin flows may well co-exist.

In their examination of the records from the northern trench, Shor *et al.* (1979) appear to find evidence of a winter minimum in the westward transport, and attribute it to a summer minimum in the overflow of Norwegian Sea Deep Water, with a 6-month transit time between the Iceland-Scotland Ridge and the CGFZ. If they are correct then our records, running from late October to early July, have also oversampled this winter minimum in westward transport. However, although Figure 3 shows a clear peak in the eastward flow in late January (net daily transport

~ 1 Sv), there is no evidence of a seasonal signal in these data; further, Harvey's examination of 101 deep hydrocasts at Ocean Weather Station "Charlie" from 1964 to 1973 shows that there is little seasonal variation in the value of the salinity maximum which marks the core of the overflow water in the northern trench (Harvey, 1980). An equal possibility is that Shor *et al.* have *over*-estimated the westward flow through the northern trench by assuming that the flow along the north side of that trough (Woods Hole mooring 572) is representative of the flow along its south wall. The only available record from that south wall was one of 35 h duration in July 1975 (Station "1CM" of Shor *et al.,* 1979) and while it did not show the eastward drift characteristic of the southern trench, it registered only a weak westward flow.

The current meter records from the southern trench also provide indirect information on the question of flow through the median ridge from the southern to the northern trench. On the basis of their short-term current meter records 1CM-3CM and on current directions inferred from bedforms, Shor *et al.* provide evidence of a northwesterly rather than westerly flow in the deepest layers of the northern trench at 35°05′W-35°13′W, a little to the west of a deep gap in the median ridge (longitude 34°30′W; sill depth ~ 3300 m). Since meters 1CM and 2CM lie in water of western origin they suggest that this northward flow component is caused by Newfoundland Basin Water spilling into the northern trench through the median ridge, with subsequent westward entrainment. In the southern trench, however, well to the east of this gap, we find that the eastward flowing water is still held tightly against the south wall, and that the north wall is blanketed by westward flowing water from 3000 m (or shallower) to the bottom. Held against the north wall by Coriolis force, it is likely that the upper part of this westbound flow will transfer to the northern trench on reaching the gap in the median ridge at 34°30′W. If so, it may well produce the northward component of flow which Shor *et al.* describe, either directly or by entrainment, as it crosses the northern valley to merge with the main body of overflow water.

A part of the eastward flow along the south wall of the southern trench is likely to meet a similar fate a little to the east of our section where it encounters the median valley of the Mid Atlantic Ridge. Searle (1979) shows that this median valley breaks into the southern trough at around 30W, forming a gap in the south wall that is as wide and as deep (at that point) as the southern trough itself, with a sill depth of > 3500 m.

5. Low-frequency fluctuations

Following Schmitz and Hogg's (1978) analysis of long-term records from the northern trough, spectral properties of the low-frequency segment of our data were examined using (in this case) a uniform record of 228 daily values from four

Table 3. Eddy kinetic energies ($cm^2\ s^{-2}$) for the indicated records and ranges of periods (τ, days), southern trough.

Record	Band 1 ($52 \leq \tau \leq 456$)	Band 2 ($17 \leq \tau \leq 52$)	Band 3 ($8.3 \leq \tau \leq 17$)	Band 4 ($2 \leq \tau \leq 8.3$)	k_E (T) Bands 1-4 ($2 \leq \tau \leq 456$)
$A_{(U)}$	2.1	3.3	2.4	0.8	8.6
$B_{(U)}$	18.1	6.6	1.8	1.1	27.6
$B_{(B)}$	1.2	3.4	3.9	1.2	9.7
$C_{(B)}$	0.2	1.0	0.6	0.3	2.1

of the five meters. Table 3 lists eddy kinetic energies for four adjacent frequency (ν) bands covering the entire range of "eddy" frequencies accessible in our data $\left(\frac{1}{456} - \frac{1}{2} \text{ cpd}\right)$. In the above table the total eddy kinetic energy ($k_E(T)$) differs slightly from that listed in Table 2b, due to the truncation of the records from 247 to 228 d.

The mean spectral estimate in each band was then divided by $\log_{10} \frac{\nu_2}{\nu_1}$, where ν_1 and ν_2 represent the low and high frequency limits of each band, respectively. When plotted against $\log_{10} \nu$, this provides spectral plots which are energy preserving by area (Fig. 4).

The eddy kinetic energy levels described in Tables 2b and 3 have many similar features to those reported by Schmitz and Hogg from the northern trench. k_E varies by an order of magnitude. In relative terms, values of k_E exceed those of k_M by well over an order of magnitude at the upper meters on each mooring, remote from the valley walls, and are more nearly equivalent to k_M at each of the near-bottom meters where steady (constrained) flows prevail; in absolute terms the highest values of k_E encountered in this area of extreme topographic roughness are higher than those normally found in the Atlantic at this depth range, outside the Gulf Stream region (Emery and Dickson, in prep.).

At each of our moorings the data are restricted to two levels in the vertical compared with up to four levels in the northern trench. However, the energy-preserving kinetic energy frequency spectra are at least consistent with the results of Schmitz and Hogg, in that the spectra from the center and south wall of the valley appear to contain relatively more energy at shorter time scales with increasing depth (Fig. 4). Maximum energy is in the 52-456 d period band at 3000 m, in the 17-52 d period band at 3500 m and in the 8.3-17 d period band at 4000 m (nominal depths). This change in spectral shape with depth is very much more exaggerated than in the northern trench. In the latter an essentially red spectrum is found at 1000 m depth (cf 3000 m in our data) and there is a slower shift of energy to higher

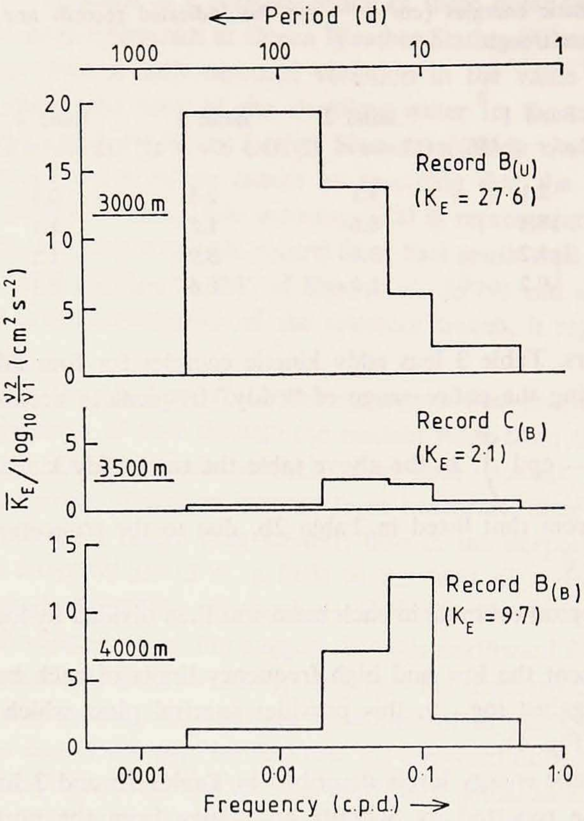

Figure 4. Plots of decadal spectral estimates (energy preserving by area) for the indicated records and depths (nominal). The four frequency bands are those described in the text and listed in Table 3.

frequencies with depth below that level, resulting in an energy maximum in the 17-48 d band at 4200 m (but in the 8.3-17 d band at 4000 m in our data). Despite this, the vertical distributions of k_E *within* each of the four frequency bands are found to be surprisingly similar, in terms of their rates of increase or decrease with depth, when results from the central parts of each trough are compared. Figure 5 shows these distributions for the two records at mooring B (southern trough) and for the four records at mooring 572 (northern trough; data from Schmitz and Hogg (1978)). In both sets of data, k_E for the lowest frequency bands increases sharply upward while the highest frequencies are bottom intensified.

Partitioning the total eddy kinetic energy ($k_E(T)$) for mooring 572 into its total zonal and meridional components ($\overline{u'^2}$ and $\overline{v'^2}$) Schmitz and Hogg show that most of the vertical variation in $k_E(T)$ at this mooring is determined by the cross-isobath flow since the individual values of $\overline{u'^2}$ are essentially constant with depth. This does

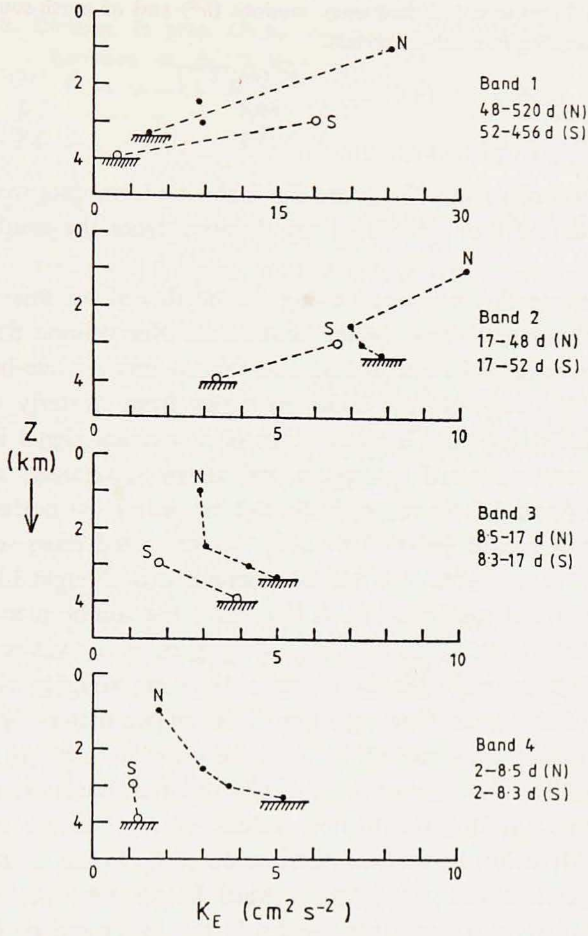

Figure 5. Vertical distributions of eddy kinetic energy (k_E) wtihin four adjacent bands of periods for moorings in the central parts of the northern (N) and southern (S) troughs. Open circles describe data from mooring B, southern trough; dots describe results from Woods Hole Mooring 572, northern trough (data from Schmitz and Hogg, 1978). The period limits of each band (d) are indicated for each set of records.

not appear to be the case for mooring B at the corresponding point in the southern trench; though we have only two depths of observation at this mooring they show clearly enough that both $\overline{u'^2}$ and $\overline{v'^2}$ decrease markedly with depth (Table 4).

6. Summary and conclusions

Long-term (250 d) current meter records were obtained from an array of three moorings (two meters per mooring) set across the southern trough of Charlie-Gibbs

Table 4. Variance of east-west low frequency motions ($\overline{u'^2}$) and of north-south low frequency motions ($\overline{v'^2}$) at mooring B, southern trench.

	$\overline{u'^2}$ (cm^2 s^{-2})	$\overline{v'^2}$ (cm^2 s^{-2})
Record $B_{(U)}$	60.8	7.3
Record $B_{(B)}$	15.7	3.8

Fracture Zone, west of its sill. These are the first long-term data from the southern trough and include the first records of any duration from the south wall of either valley.

Mean flows are steadily westward along the north wall of this valley and persistently eastward along the base of the south wall. Net volume transport for that part of the section covered by our instruments (approximately one-half of the cross-sectional area of the valley below 2000 m) varies from westerly to easterly with a 2-3 month periodicity. There is no evidence of a seasonal signal in net transport. Mean westward and eastward transports, calculated separately, show maximum daily values of 0.7 and 1.0 Sv respectively, but are in almost perfect balance over the whole period of record (~ 0.24 Sv over this restricted cross-section). In their respective downstream directions from this section, it is thought likely that a part of these westbound and eastbound flows will leave the southern trough, under the influence of Coriolis force, where they meet deep gaps in the valley walls.

Close to the bottom, eddy kinetic energies (k_E) are roughly equivalent to the kinetic energies of the mean flow (k_M) but at the upper meters on each mooring, remote from the steady (constrained) flows at the walls, k_E exceeds k_M by well over an order of magnitude. In common with results reported from the northern trough (Schmitz and Hogg, 1978), the highest values of k_E indicate a comparatively energetic deep eddy field; the vertical distribution of k_E in the center of the trench is frequency dependent being weighted toward longer time scales in the upper record ($B_{(U)}$) and toward shorter time scales in the lower record ($B_{(B)}$); although this shift in energy from the secular to the mesoscale (or higher) with depth appears to be more exaggerated than in the corresponding (central) part of the northern trench, the relative rates of change of k_E with depth show elements of similarity to those reported by Schmitz and Hogg, when the total eddy kinetic energy ($k_E(T)$) is partitioned into four component frequency bands. k_E for the lowest frequency bands increases sharply upward, while the highest frequencies are bottom intensified.

Acknowledgments. We thank John Gould for computational assistance during the analysis of these records, Gordon Baxter for supervising the deployment and recovery of the moorings and the Master and Crew of R.V. *Cirolana* for their precise work under persistently gale-force conditions.

REFERENCES

Cooper, L. H. N. 1955. Deep water movements in the North Atlantic as a link between climate changes around Iceland and biological productivity of the English Channel and Celtic Sea. J. Mar. Res., *14,* 347–362.

Emery, W. and R. Dickson. In prep. Global summaries and intercomparisons, *in* Eddies in Marine Science, A. Robinson, ed., SCOR WG 34.

Garner, D. M. 1972. Flow through the Charlie-Gibbs Fracture Zone, mid-Atlantic Ridge. Canadian Jour. of Earth Sci., *9,* 116–121.

Harvey, J. G. 1980. Deep and bottom water in the Charlie-Gibbs Fracture Zone. J. Mar. Res., *38,* 173–183.

Harvey, J. G. and A. N. Shor. 1978. Norwegian Sea overflow water in the Charlie-Gibbs Fracture Zone. ICES CM 1978/C:62, 6 pp + 6 figs. (mimeo).

Le Pichon, X., S. Eittreim and J. Ewing. 1971. A sedimentary channel along Gibbs Fracture Zone. J. Geophys. Res., *76,* 2891–2896.

Neumann, G. 1968. Ocean currents. pp. 53-54: Elsevier 352 pp. (Elsevier Oceanography Series, No. 4).

Ramster, J. W., D. G. Hughes and G. K. Furnes. 1978. A "steadiness" factor for estimating the variability of residual drift in current meter records. Dt. Hydrogr. Z., *31,* 230–236.

Schmitz, W. J., Jr. 1974. Observations of low frequency current fluctuations on the Continental Slope and Rise near Site D. J. Mar. Res., *32,* 233–251.

Schmitz, W. J., Jr. and N. G. Hogg. 1978. Observations of energetic low frequency current fluctuations in the Charlie-Gibbs Fracture Zone. J. Mar. Res., *36,* 725–734.

Searle, R. 1980. The active part of Charlie-Gibbs Fracture Zone, a study using sonar and other geophysical techniques. J. Geophys. Res., in press.

Shor, A., P. Lonsdale, C. D. Hollister and D. Spencer. 1980 Charlie Gibbs Fracture Zone: bottom water transport and its geological effects. Deep Sea Res., in press.

Worthington, L. V. and G. H. Volkmann. 1965. The volume transport of the Norwegian Sea outflow in the North Atlantic. Deep Sea Res., *12,* 667–676.

Worthington, L. V. and W. R. Wright. 1971. Discussion of a paper by X. Le Pichon, S. Eittreim and J. Ewing: "A sedimentary channel along Gibbs Fracture Zone". J. Geophys. Res., *76,* 6606–6608.

Received: *3 December, 1979;* revised: *3 April, 1980.*