A Preliminary Exploration of the Gulf Stream System with SOFAR Floats

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ABSTRACT

SOFAR (sound fixing and ranging) floats deployed for engineering tests during 1977–79 yield the first long-term quasi-Lagrangian observations in the subsurface Gulf Stream System. The character of these float tracks supports the premise that the Gulf Stream is a persistent, large-scale, vertically coherent jet at depths (approximately) within and above the main thermocline, where mean and eddy kinetic energies are roughly the same and lateral motions of the Stream are clearly delineated. A float track at thermocline depth is visually coherent with the track of a concurrently launched surface drifter over the larger horizontal scales traversed during the first few months of their trajectories. Below thermocline depths, fluctuation or eddy kinetic energies are normally larger than the mean and a persistent Gulf Stream is difficult to detect. However, deep motions that are visually coherent with upper level flows may be observed for an intermediate range of space and time scales.

Eddy kinetic energies based on the float data are compatible with existing Eulerian estimates to the extent comparable. The consistency of a quasi-Lagrangian eddy kinetic energy estimate in the vicinity of the thermocline, roughly 400 cm^2 s^{-2}, the first such observation to our knowledge, is indirect but relatively convincing. Zonal and meridional variances for the float data are also in line with existing Eulerian results. Estimates of the frequency distribution of eddy kinetic energy for the longest float trajectory available are nearly identical to comparable Eulerian results at frequencies less than about a cycle per 20 days.

1. Introduction

The nature of the Gulf Stream System has been a subject of intense inquiry and frequent controversy throughout the history of oceanography, and remains so to this day (Clarke et al., 1980; Fofonoff, 1981; Hendry, 1981; Schmitz, 1977, 1978, 1980; Stommel, 1965; Worthington, 1976). For the first time, neutrally buoyant (SOFAR) floats have been deployed and tracked acoustically over relatively long times and distances in the vicinity of the Stream. These floats, launched primarily as engineering tests of tracking capability, were positioned from data obtained from both land-based and moored listening stations. The purpose of this note is to present a preliminary description of results based on the five subsurface trajectories obtained, along with a contemporaneous surface drifter path. We first examine the cohesive nature of the flow in the thermocline and upper layers of the Gulf Stream, relative to the more chaotic flow observed near the Stream at abys-sal depths, where perturbation (or eddy) kinetic energies are normally larger than the mean. We then focus on estimates of eddy energy levels. At depths below the thermocline, this, the first such inter-comparison in the vicinity of the Gulf Stream, yields quasi-Lagrangian perturbation kinetic energy levels and an associated frequency distribution that are remarkably compatible with those based on Eulerian data.

2. Background

Neutrally buoyant, acoustically tracked floats were initially developed by Swallow (1955, 1957) and subsequently used in a variety of influential observational programs, all based on shipboard tracking. Prominent examples are the first direct measurements identifying an abyssal undercurrent along the western boundary of the North Atlantic (Swallow and Worthington, 1961), and results from the ARIES Expedition that initially demonstrated the existence

of a comparatively energetic mesoscale eddy field in the North Atlantic southwest of Bermuda (Crease, 1962; Swallow, 1971). The short-term float observations at abyssal depths conducted during Gulf Stream '60 (Fuglister, 1963) led Worthington (1976) to postulate a vertically coherent and persistent Gulf Stream with relatively large abyssal currents in the same direction as in the upper layers, leading to a consequently large transport. However, the persistence of a Gulf Stream at abyssal depths has not been easy to reconcile with the relatively large-amplitude time-dependent currents that have consistently been observed there over the last decade or so, beginning with Fofonoff (1967) and Schmitz et al. (1970). The existence of the largest eddy kinetic energies (per unit mass, hereafter understood, symbol K_E) at all depths in the vicinity of the Stream is now one of the most clearly established properties of the eddy field in the western North Atlantic. These results suggest that abyssal currents near the Gulf Stream cannot always be visualized as part of a vertically coherent structure. Long-term float observations for examination of the typicality of the (roughly) week-duration data obtained at abyssal depths during Gulf Stream '60 have been needed for some time.

Floats that can be tracked from shore stations over long distances with lifetimes of a few years were developed by Rossby and Webb (1970) and by Rossby et al. (1975). These SOFAR floats were first used in quantity in a mid-ocean dynamics experiment (Freeland et al., 1975; McWilliams, 1976). Several floats were deployed in Gulf Stream rings shortly thereafter (Cheney et al., 1976), and some later moved into the Gulf Stream, but were followed there for short periods of time only (roughly two weeks). SOFAR floats were next used in quantity in the western basin of the North Atlantic both south and north of the MODE area (McDowell and Rossby, 1978; Price and Rossby, 1981; Riser et al., 1978; Riser and Rossby, 1981). The recent development of moored (Autonomous) Listening Stations (ALS's; Bradley, 1978) removes the limitations on the area of operation imposed by land-based tracking.

Many surface drifters have been tracked in the Gulf Stream System in recent years (Kirwan et al., 1976; Richardson et al., 1979; Richardson, 1980, 1981). These paths provide clear evidence for the persistence and large horizontal scale of the upper level Stream west of the Grand Banks. Drifter trajectories have been observed to be strongly influenced
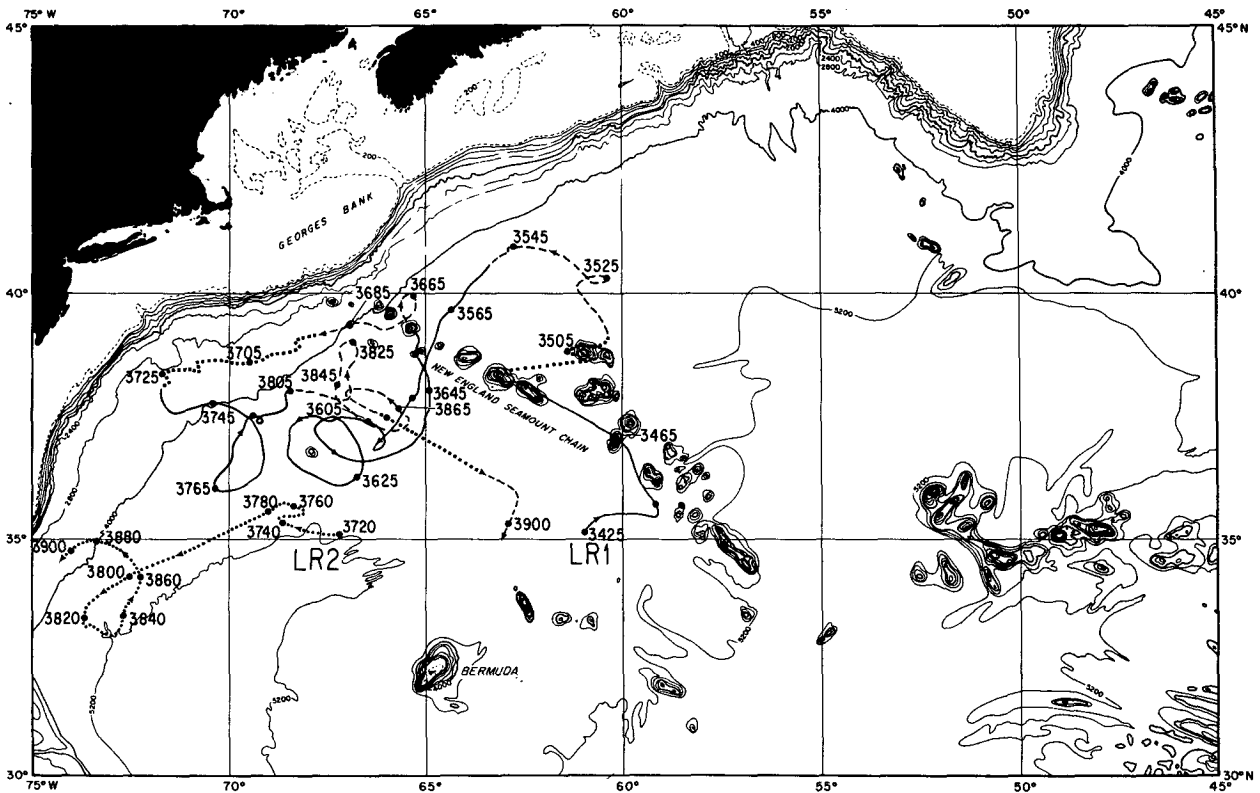

FIG. 1. Trajectories for floats LR1 and LR2, as indicated. Numbers next to the tracks denote time as a day number: see Table 1 for control information. The quality of the position fixes for LR1 varied considerably: solid lines indicate good quality; solid squares, intermediate quality; dashes, poor quality.

TABLE 1. Basic trajectory characteristics.

Float I.D.	Launch date	Launch day (modified Julian)	Duration tracked (days)	Approximate launch position	Design pressure (db)	Average pressure $\bar{p}$ (db)	rms pressure variation $(\overline{p'^2})^{1/2}$ (db)	Mean zonal speed $\bar{u}$ (cm s⁻¹)	Mean meridional speed $\bar{v}$ (cm s⁻¹)	Zonal variance $\overline{u'^2}$ (cm² s⁻²)	Meridional variance $\overline{v'^2}$ (cm² s⁻²)	Mean temperature $\bar{T}$ (°C)	Temperature variance $\overline{T'^2}$ (°C)
LR1	9 Oct 1977	3425	476	35.0°N, 61.0°W	1300	1207	39	-0.4	0	188	126	*	*
LR2	29 Jul 1978	3718	281	35.0°N, 67.0°W	1300	*	*	-2.3	0	60	37	*	*
C72	6 Jun 1979	4030	122	38.4°N, 67.9°W	700	758	39	8.0	0	562	384	9.65	2.40
C73	6 Jun 1979	4030	204	38.4°N, 67.9°W	1300	1500**	*	0.5	-2.3	102	48	4.19	0.24
C74	6 Jun 1979	4030	168	38.4°N, 67.9°W	2000	2034	17	4.0	-2.1	154	107	3.81	0.07
D12	7 Jun 1979	4031	114	38.5°N, 67.8°W	surface drifter	*	*	17.7	-2.9	2780	2575	*	*

* Information not available.
** Off telemetry scale.

by the New England Seamounts (Richardson, 1981) and the Corner Rise (Richardson, 1980). A drifter that traversed the Kuroshio System showed similar sensitivity to topography (Cheney et al., 1980). The influence of topography on the float and drifter trajectories described in the following is in general reminiscent of Richardson's results with drifters.

Worthington's division (1976) of the subtropical gyre circulation outside of the Gulf Stream into two scales of motion with one confined roughly to latitudes north of Bermuda (most prominently at abyssal depths), here called the recirculation, has been independently substantiated (Schmitz, 1976, 1977, 1978, 1980). However, Worthington's (1976) hypothesis of an ageostrophic recirculation (at the leading order of approximation) has been shown by Stommel et al. (1978) to be unnecessary, and even another type of geostrophic recirculation has been suggested by Schmitz (1980). The combination of the Gulf Stream and recirculation will be referred to as the Gulf Stream System. The circulation in the subtropical gyre south of the recirculation will be called the return flow. In the following, we will use the nomenclature referred to in the previous sentences in this paragraph, but without implying adherence to all elements of the circulation model proposed by Worthington (1976). Fofonoff (1981) has recently summarized the nomenclature and status of knowledge of the structure of the Gulf Stream System.

3. Discussion

SOFAR floats (and surface drifters) are nearly isobaric rather than isopycnic, and hence a float track is not an exact water particle path. The spirit of our treatment and discussion of this type of quasi-Lagrangian data is in terms of mobile current sensors rather than literal water particle path-sensing devices, in some analogy to the approach taken by Freeland et al. (1975). The statistics that we compute are then simply mixed spatial and temporal averages. This paragraph contains our working version of the term "quasi-Lagrangian".

The floats signal three times each day. Position data are smoothed with a 2-day half-width Gaussian taper, and center-differenced to yield velocity. Signal detection and processing details, along with associated errors, have been described by Spain et al. (1980). Position errors are ~5 km, with a fix-to-fix random error of ~1 km. In addition, changes in tracking net due to changes in choice of listening station net are persistently observed to lead to position changes of 10 km. We also have significant signal dropout and more serious tracking errors when operating at the limit of signaling reception range. The net velocity error is frequency dependent, being higher at higher frequencies, and the relative velocity error is displacement dependent.

Preparation for gyre-scale exploration with SO-FAR floats included tests of ALS tracking capability in the most energetic segments of the North Atlantic, including the Gulf Stream System. These data form the basis of the present investigation (Table 1). The initial engineering test float, called Long-Range 1 (LR1), was set in the recirculation area in 1977. LR2 was deployed 6° longitude to the west about nine months later (Fig. 1, Table 1). LR1 yielded the long-est term trajectory obtained in our test sequence, being followed for roughly 16 months over a wide range of positions, although with varying tracking quality, in the vicinity of the Gulf Stream System and in Slope Water. The performance of LR1 and LR2 indicated that the range (~2000 km) needed for deployments on basin scale with a manageable number of receiving stations was achievable with some additional modifications. After redesign based on the experience gained with LR1 and LR2, as well as evaluations of an evolving ALS configuration, additional trials (involving ALS's on both sides of the Stream) were implemented in June 1979. This test sequence was initiated with the deployment of floats G72, G73 and G74 (G denotes Gulf Stream) at a location 25–35 km south of the Stream axis (as determined by XBT data) in the vicinity of 38°N. A satellite-tracked surface drifter (D12) was launched

at about the same time and location. This drifter was located using data from Nimbus 6 (or F) and was deployed with 35 m of line between the drifter hull and a window-shade drogue. Basic data for the floats and surface drifter launched in the Gulf Stream are listed in Table 1 and trajectories shown in Figs. 2 and 3. For reference, the mean position of the 15°C isotherm at 200 m (from Schroeder, 1963), used as an index for the Stream axis (Fuglister and Voorhis, 1965), is plotted in Fig. 4 on the same scale as in Figs. 1–3. Bottom topographic contours on Figs. 1–4 were taken from Uchupi (1971); Fig. 4 contains bathymetric detail that was suppressed in Figs. 1–3 in order to present a relatively unencumbered visualization of float and drifter trajectories.

The trajectories in Figs. 1–3 illustrate a complexity consistent with existing Eulerian data (Hendry, 1981; Luyten, 1977; Schmitz, 1976, 1977, 1978, 1980) which typically yield eddy kinetic energies larger than the mean at abyssal depths in the vicinity of the Gulf Stream. At the lowest frequencies, LR1 is circulating cyclonically (Fig. 1), appearing to "cross" or "go through" the Gulf Stream at least twice. While in the Slope Water region, the mean flow for LR1 is to the west, agreeing with all (even moderately) long-term moored instrument observations there, beginning with Webster (1969). However, this flow
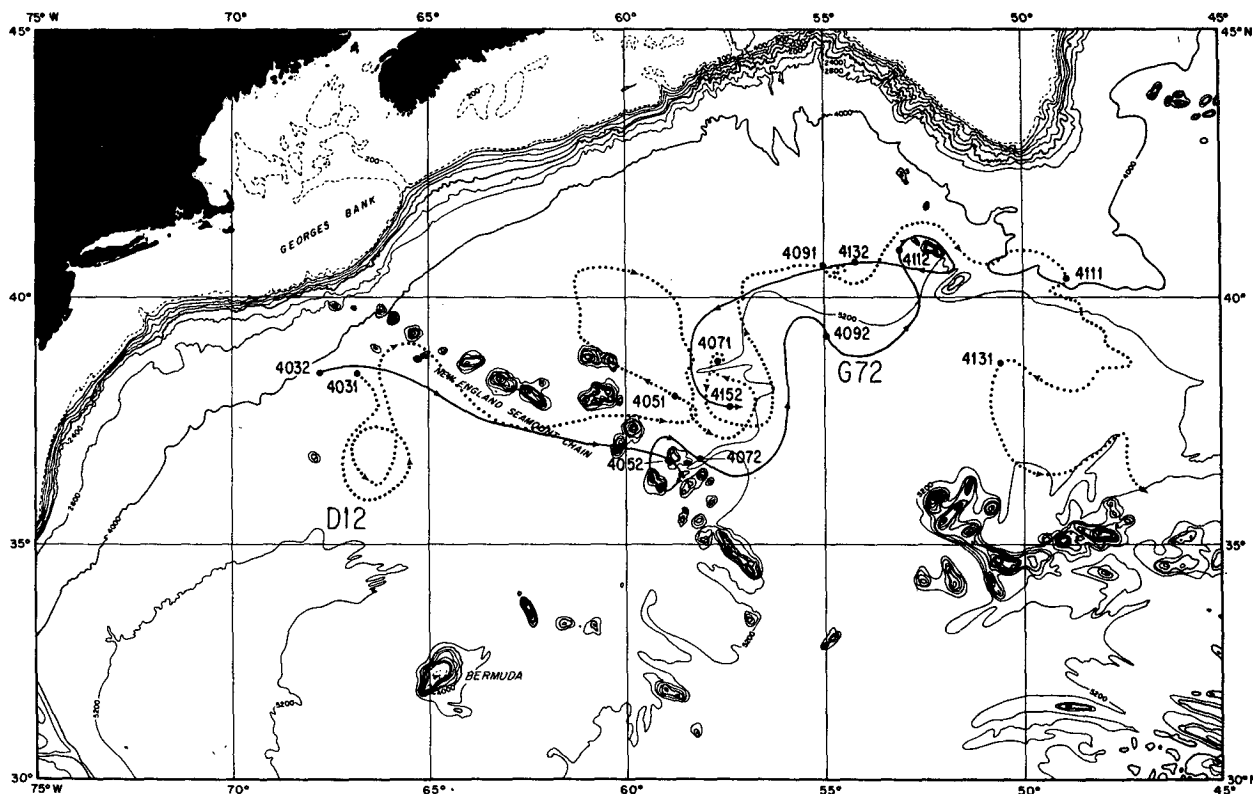

FIG. 2. Trajectories for float G72 and surface drifter D12. Numbers next to the tracks denote time as a day number: see Table 1 for control information.
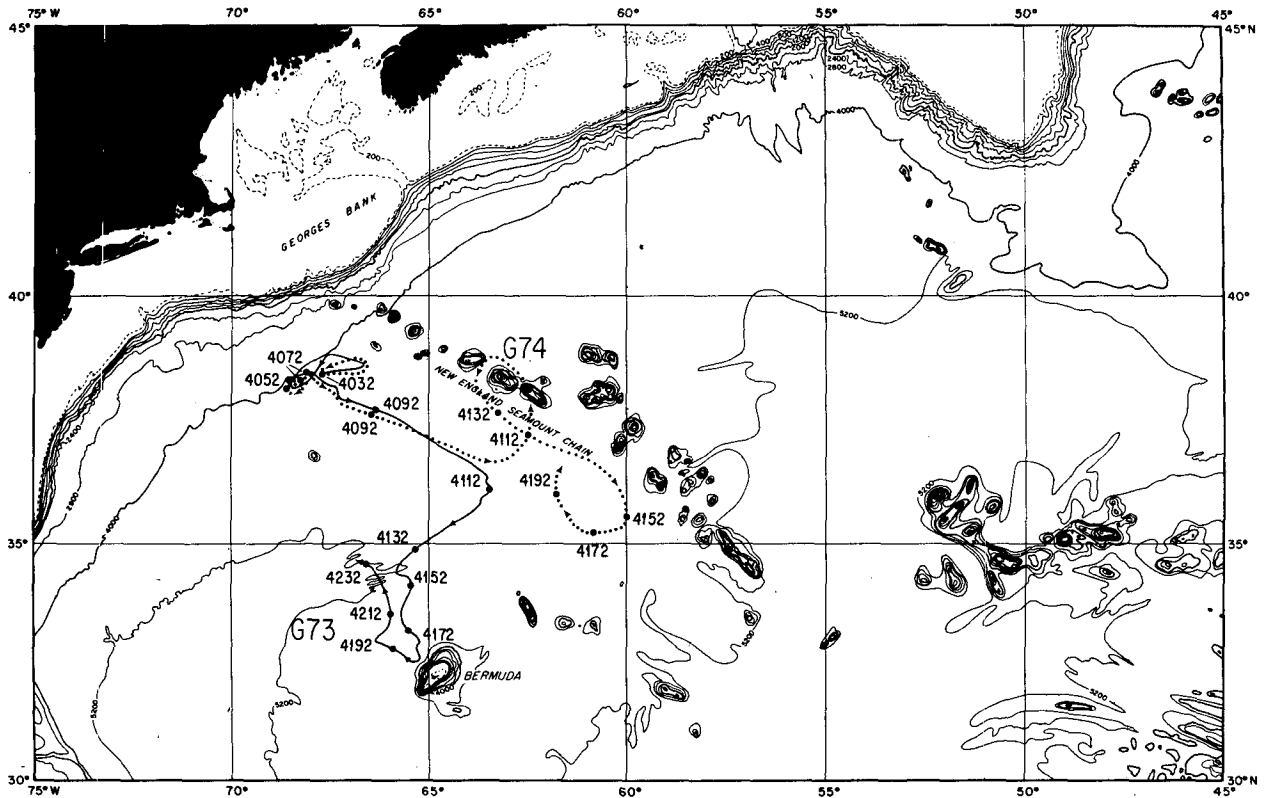
FIG. 3. Trajectories for floats G73 and G74. Numbers next to the tracks denote time as a day number: see Table 1 for control information.
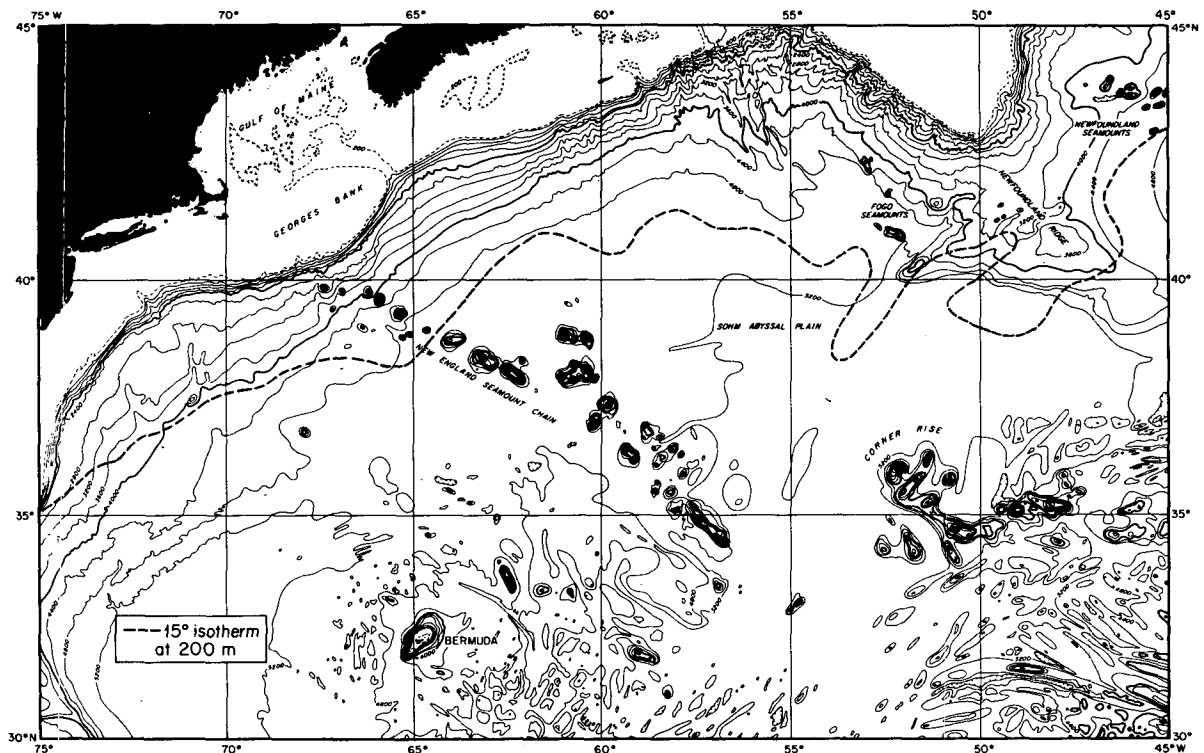

FIG. 4. Mean position of the 15°C isotherm at 200 m depth (according to Schroeder, 1963).
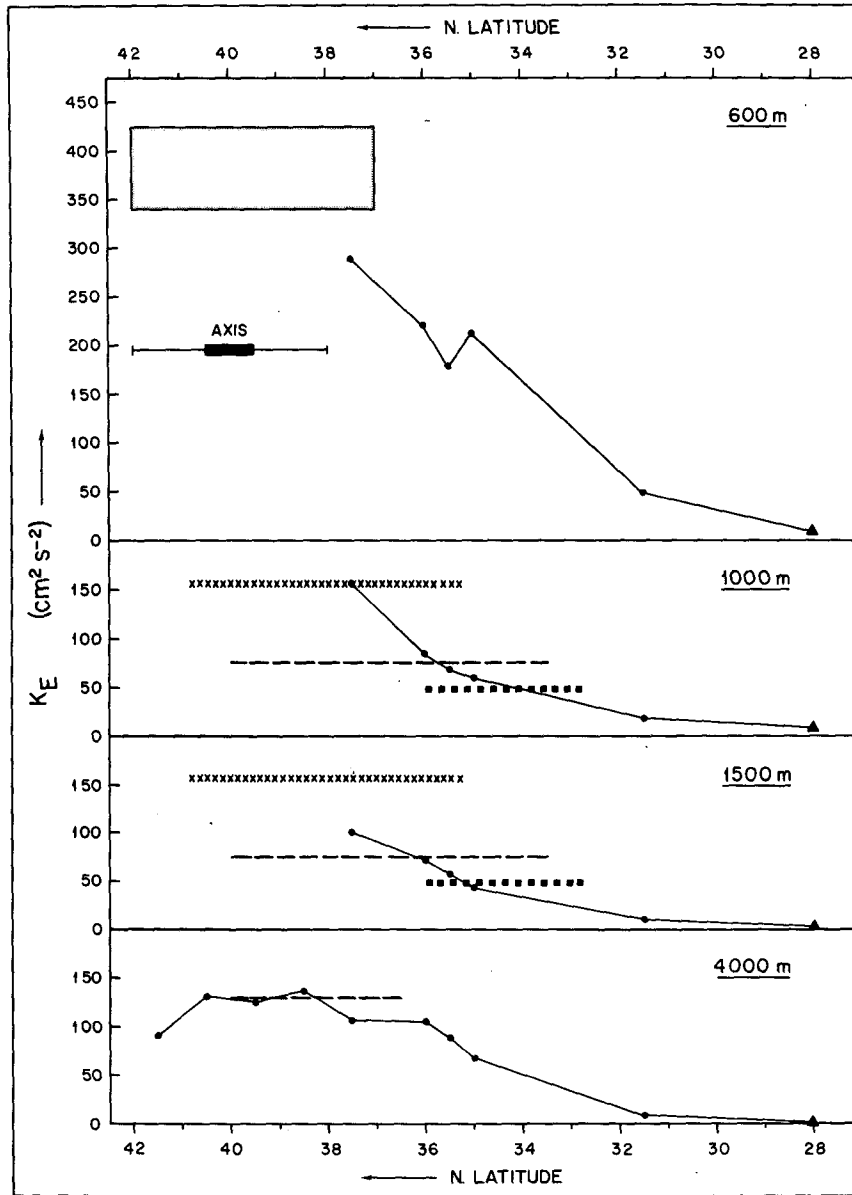
Fig. 5. Eddy kinetic energy (K_E) as a function of latitude for Eulerian data for four depths along 55°W and for the floats in Figs. 1–3. The moored instrument data (Schmitz, 1978; Schmitz and Holland, 1981), located at the four depths shown to the right in each panel or frame, are connected by a solid line. Data for floats are denoted by: a dashed line in the 4000 m frame for G74; a dashed line for G73, solid squares for LR2, and crosses for LR1, all in both the 1000 and 1500 m panels; G72 by a shaded box in the 600 m frame. A range of positions for the axis of the Gulf Stream is shown in the upper panel: the solid bar is appropriate to 55°W, the bracketed line spans the latitude range appropriate to the floats.

regime is not contained in Worthington's (1976) circulation diagrams. LR1 moves both west and east while near the expected location of the Gulf Stream, reminiscent of Eulerian data. LR2 exhibits the "expected" behavior for the recirculation regime, moving westward at a few centimeters per second on the average until reaching the vicinity of the Gulf Stream and Cape Hatteras, where tracking was lost

due to shore-based listening station failure. The thermocline float (G72) and surface drifter launched near 67–68°W in the Gulf Stream (Fig. 2) move in a relatively coherent pattern on the largest scale for ~70 days over about 1300 km, evidently staying in the vicinity of a visually clear-cut Stream until in the vicinity (52–53°W) of the Fogo Seamounts (Fig. 4). G72, which telemetered temperature, traversed

much colder water after leaving the Fogo Seamounts, as expected in Slope Water where the temperature at the float was observed to be ~6°C, in contrast to 10–12°C while in the Gulf Stream. Although D12 and G72 both moved south of east along the New England Seamounts, and looped north to the Fogo Seamounts, their intermediate horizontal-scale behavior is not similar. The early cyclonic movement of D12 was due to the presence of a documented ring (Cummings et al., 1979). D12 is apparently also influenced by a meander-ring pattern near about 56–61°W [also seen in the temperature field by Blumenthal and Gotthardt (1979) and by Cummings et al. (1979)]. None of this is exhibited in any detail by the G72 trajectory, although there is a connection to a meander pattern on the largest scale in the vicinity of 56–61°W. G73 and G74 also moved coherently over the first 70–80 days of their deployment (Fig. 3), and, after initially being caught in a small-scale feature not exhibited by G72, moved in the same direction as G72 but at a slower speed. All floats as well as the surface drifter were noticeably affected by the New England Seamounts, much as previously observed and described by Richardson

(1981), and perhaps rationalized to some extent by Owens and Hogg (1980). The tracks for G73 and G74 diverge sharply from each other as well as from the tracks of G72 and D12 in the vicinity of the New England Seamount Chain, with neither deep float clearly crossing the seamounts like the upper level drifters. The trajectory from the vicinity of the New England Seamounts for float G74 (Fig. 3) is reminiscent of the trajectory of LR1 (Fig. 1) while the latter was in the same region. The sum of the trajectories for LR1, G73 and G74 may imply that the abyssal flow in the vicinity of the Gulf Stream does not penetrate (is blocked), or only partially penetrates (is to some extent blocked) east of the New England Seamounts. Other evidence for this type of flow regime is discussed by Schmitz (1980) and Richardson (1981, see especially Fig. 2).

Basic statistics for the trajectories are contained in Table 1. Eddy kinetic energies are shown in Fig. 5, and zonal and meridional variances in Figs. 6 and 7. The float statistics in Figs. 5, 6 and 7 are plotted along with the only existing latitudinal section (at 55°W) of Eulerian time averages at both abyssal and thermocline depths (Schmitz, 1978; an

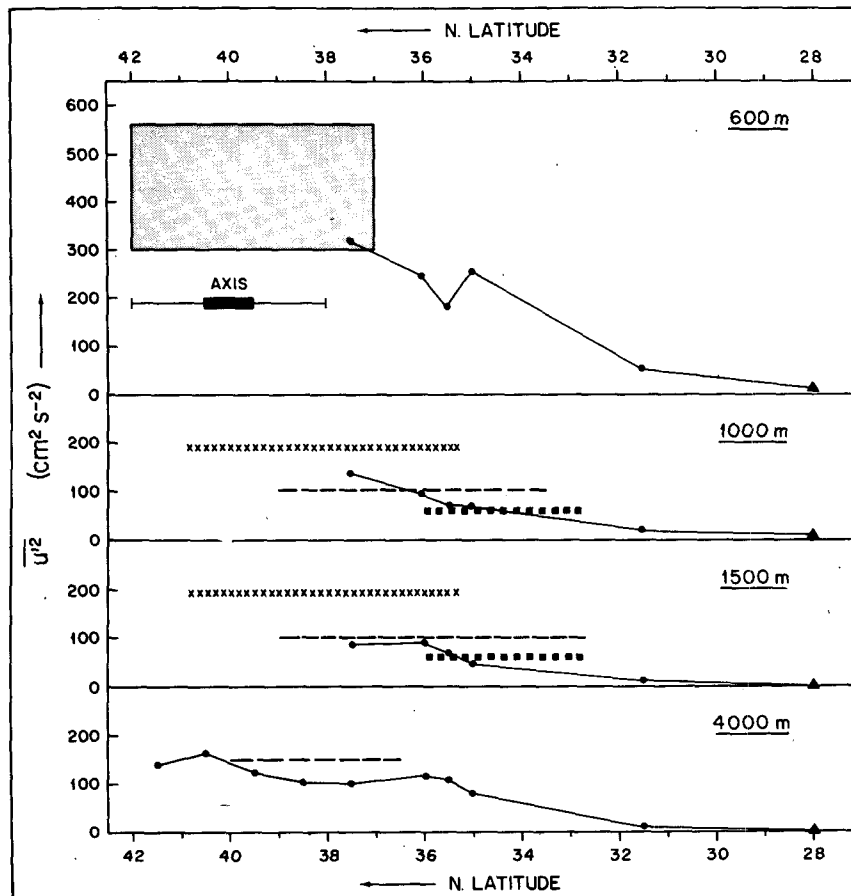FIG. 6. As in Fig. 6 except for zonal variance $(\overline{u'^2})$.

FIG. 7. As in Fig. 6 except for meridional variance $\overline{(v'^2)}$.

updated version is contained in Schmitz and Holland, 1981; see, also, Hendry, 1981). The symbols $\overline{u'^2}$ and $\overline{v'^2}$ are used for zonal and meridional variances: $K_E = 0.5(\overline{u'^2} + \overline{v'^2})$. The prime denotes a deviation from the overbarred average (with this average taken along a trajectory for a quasi-Lagrangian quantity, in time at a point for Eulerian data). $\bar{u}$ and $\bar{v}$ denote zonal and meridional mean flows respectively. In Figs. 5–7, quasi-Lagrangian K_E and variances are plotted as values that extend over the latitude range traversed by the floats, and in the case of the thermocline float G72, also over the range of K_E resulting from different plausible choices of averaging interval.

The float K_E values in Fig. 5 are generally consistent with the Eulerian estimates, perhaps remarkably so, and this also holds true for the distributions of zonal and meridional variance in Figs. 6 and 7. LR1 results agree least with the Eulerian data, being generally higher. In the frequency distributions of Fig. 8 the only significant difference between the LR1 estimates and a comparable Eulerian distribution occurs for periods of 2–20 days. This period

range is the primary locus of tracking noise [see also Fig. 10, p. 400 in Freeland *et al.* (1975)], expected to be relatively large for LR1, which operated at the limit of positioning range over much of its lifetime, and in general is the lowest quality track available. We examined the energy-frequency distribution for LR1 in some detail because it is the longest trajectory available, and therefore most appropriate for comparison with the lowest frequencies accessible with the Eulerian data. Float tracks for G72, G73 and LR2 are much shorter, although of higher tracking quality. However, stable spectral estimates for the highest frequency band (periods 2–20 days) are accessible with these floats, and result in energies that are considerably closer to the appropriate Eulerian estimates. For example, G73 yields 17 cm² s⁻² for 2–20 day periods (the Eulerian result for this frequency band in Fig. 8 is ~18 cm² s⁻²), as opposed to roughly 55 cm² s⁻² for LR1 (Fig. 8). K_E values for the surface drifter D12 are in the vicinity of 2500 cm² s⁻², more than a factor of 2 higher than might be suggested from casual examination (the averaging schemes are different) of estimates from the map
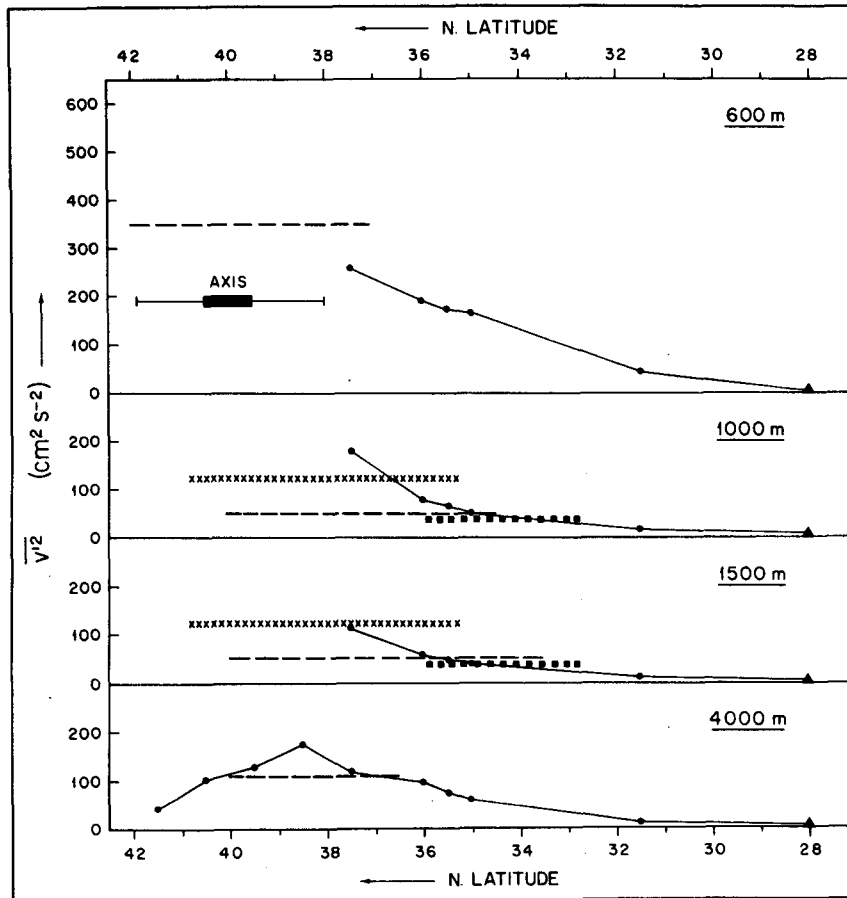
FIG. 7. As in Fig. 6 except for meridional variance $\overline{(v'^2)}$.

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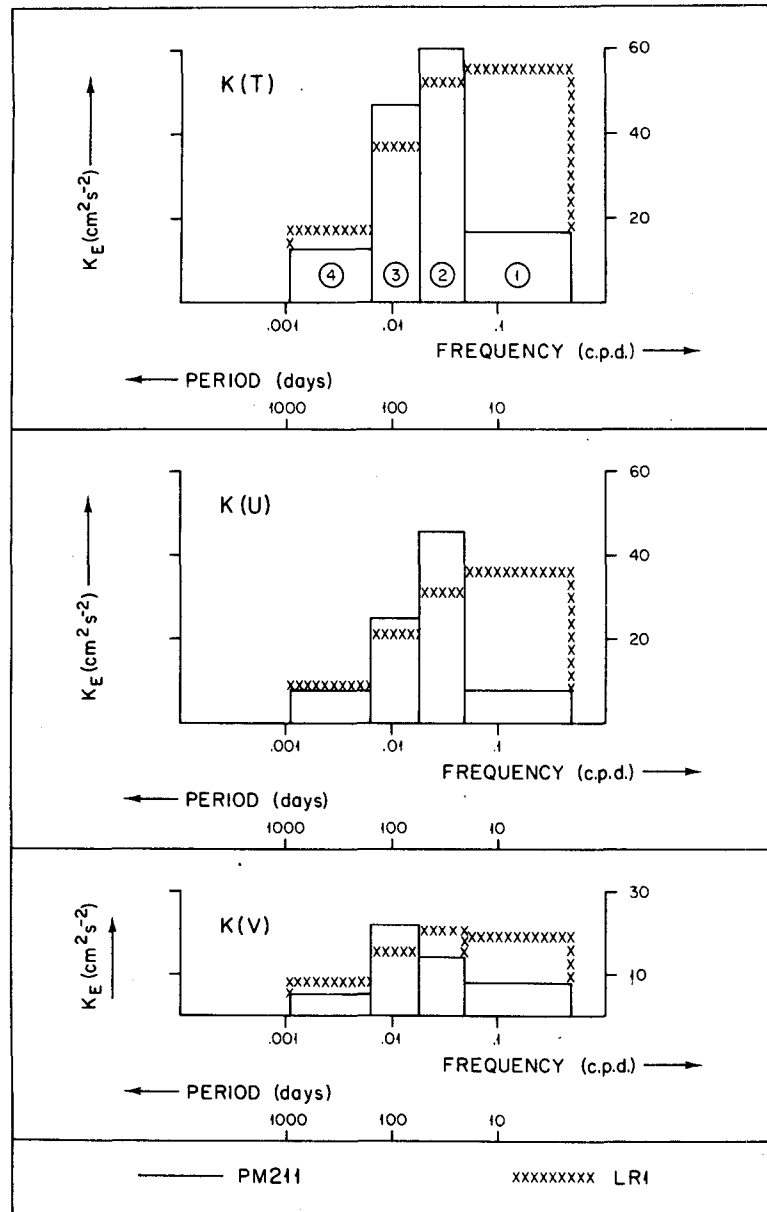
FIG. 8. Frequency distributions of eddy kinetic energy for 4000 m depth at 40°30′N, 55°W (PM211 is the label identifying this site) and for the longest float record (LR1). $K(T)$ denotes total K_E, $K(U)$ zonal, $K(V)$ meridional. The period ranges (nominal) for the four frequency bands plotted are: ①, 2–20 days; ②, 20–47 days; ③, 47–157 days; ④, 157–940 days.

due to Wyrtki *et al.* (1976). These results for D12 [which are compatible with those reported by Kirwan *et al.* (1976) for another drifter] appear at the present time to be in fact indicative of averages over several drifters (Richardson *et al.*, 1979; Richardson, 1980, 1981). Values of $\bar{u}$ for D12 and G72 (18 and 8 cm s^{-1}, Table 1) are clearly appropriate to a space-time averaged Gulf Stream; averaged over a few days speed values reach 3 and 1 kt, respectively.

4. Summary and conclusions

One picture of the North Atlantic circulation (Worthington, 1976) hypothesizes (implicitly) a vertically coherent Gulf Stream, more or less always present at all depths, although of course executing meanders and forming rings at various times and locations. The Lagrangian observations presented support this picture at depths in the thermocline

and above, but not necessarily below, in qualitative agreement with the Eulerian data available.

The estimate of $\sim$400 cm^2 s^{-2} for K_E in the thermocline ($\sim$700 m) in the Gulf Stream west of the Grand Banks is the first such direct measurement to the best of our knowledge. It is compatible with extrapolation of existing Eulerian data. K_E estimates from the upper layers of the western (energetic) segment of the Kuroshio Extension (Nishida and White, 1981) are roughly 200–300 cm^2 s^{-2}. Such estimates for both of these midlatitude jets are noticeably lower than results from the upper layer of several existing numerical model runs (Holland, 1978; Schmitz and Holland, 1981). All but one Lagrangian estimate of perturbation kinetic energies below the thermocline are nearly identical to existing Eulerian estimates. The one discrepancy is shown to be dominated by differences in the highest frequency band (periods of 2–20 days), the expected locus of error in float positioning. The compatibility of this initial comparison of quasi-Lagrangian and Eulerian observations at abyssal depths near the Gulf Stream should remove any lingering doubts as to the complexity of this flow field.

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