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An estimate of bottom frictional dissipation by Gulf Stream fluctuations

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ABSTRACT

Using published values of the kinetic energy per unit mass of fluctuating motions for the deep western North Atlantic an estimate is made of the energy dissipation rate from fluctuations by bottom friction for the Gulf Stream System. It appears that bottom friction may account for all the energy input by the wind, and that this dissipation occurs in only about 20% of the areal extent of this gyre.

1. Introduction

Truly remarkable progress in understanding the subtropical wind-driven ocean circulation has been achieved since World War II. However, a basic question has remained unanswered: How is its energy dissipated? The energy input by the winds is ultimately dissipated into heat by viscosity at the microscale level. However, the pathway to the microscale from the mean flow, e.g., bottom drag, lateral friction and/or internal wave processes, has eluded identification. The purpose of this note is to demonstrate that bottom friction associated with fluctuating motions is a significant and perhaps the dissipative mechanism for the best studies of the wind-driven gyres, the Gulf Stream System.

The appropriate choice of dissipative mechanism or mechanisms to incorporate in eddy resolving circulation models (the so-called ERCM's) is of course of practical concern to numerical theorists (e.g., Holland, 1978; Harrison, 1980). The leading contenders are bottom and lateral friction (*ibid.*). However, the paucity of data has not permitted an *a priori* selection to be made. Observational studies which bear on the problem have yielded null-type results for one region of the Gulf Stream System, the Florida Current. Weatherly (1972) indicated that bottom friction under the Florida Current is not important. Similarly, lateral friction in the Florida Current also is relatively unimportant (Webster, 1965; Schmitz and Niiler, 1969; and Brooks and Niiler, 1977). For the other high current region of this gyre, the Gulf Stream (where frictional dissipation is expected to be enhanced), less is known. Strong abyssal flows have been reported near the Gulf Stream (Schmitz, 1977; Richardson *et al.*, 1981; Bird

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et al., 1982; and Weatherly and Kelley, 1982). However, the areal extent (and hence total attendant dissipation) of these flows and whether they are part of the Gulf Stream System or deep western boundary currents are not known. Lateral friction estimates inferred from data presented in Schmitz (1977) are both negative and positive. Thus it is not clear whether lateral friction has a net dissipative effect for the Gulf Stream.

In the last decade sufficient current measurements have been made to begin to chart the eddy kinetic energy for the deep, western North Atlantic. In Section 2 such a map is presented and an interpretation for its pattern proposed. Using this map, an estimate of bottom friction dissipation of fluctuating motions with periods $\gtrsim$2 days is made in Section 3. Section 4 contains a summary and a discussion.

2. The deep eddy variability

Maps of the surface eddy variability of, or including, the North Atlantic have recently become available. They are based on ship drift data (Wyrtki *et al.*, 1976), satellite altimeter data (Cheney *et al.*, 1983) and surface drifters (Richardson, 1983); the map from the last reference is reproduced in Figure 1. Consonant with the others, it shows largest values for the high speed and meander region of the Gulf Stream, and relatively low values elsewhere. Clearly, the highest values of this figure are due to the variability of the Gulf Stream.

Values of the deep (depths $\gtrsim$4000 m) eddy kinetic energy per unit mass, KE_f, for the subtropical North Atlantic west of 43W from long (duration $\gtrsim$8 months) daily (nominally) averaged current meter records are listed in Table 1 and displayed in Figure 2. For reference, the landward edge of the mean surface Gulf Stream determined by Auer (1982) is also shown. As for the near surface (Fig. 1), the KE_f values in Figure 2 are largest for the high speed and meander region of the Gulf Stream.

The larger KE_f values are also contoured in Figure 2.[2] The surface mesoscale variability patterns seen in Figure 1 (from Richardson, 1983) and in Cheney *et al.* (1983) (their Figure 3) influenced the contour pattern in Figure 2 for regions of little or no deep data. The deep contour pattern in Figure 2 is smoother than the surface patterns given in Figure 1 and in Figure 3 of Cheney *et al.* (1983). As should become apparent later, a more elaborately contoured KE_f chart would not notably enhance the dissipation estimate presented in Section 3.

Because of the qualitative similarity of Figure 2 to Figure 1 (and Figure 3 of Cheney *et al.*, 1983), it seems reasonable to attribute the deep KE_f distribution to Gulf Stream fluctuations. Below, results are presented which indicate that the similarity of Figure 2 to Figure 1 is not coincidental.

2. Similar abyssal KE_f charts with coarser resolution are found in Kupferman and Moore (1981) and Schmitz (1984). However, unlike this study, the above make no estimate of bottom frictional dissipation by the fluctuations.

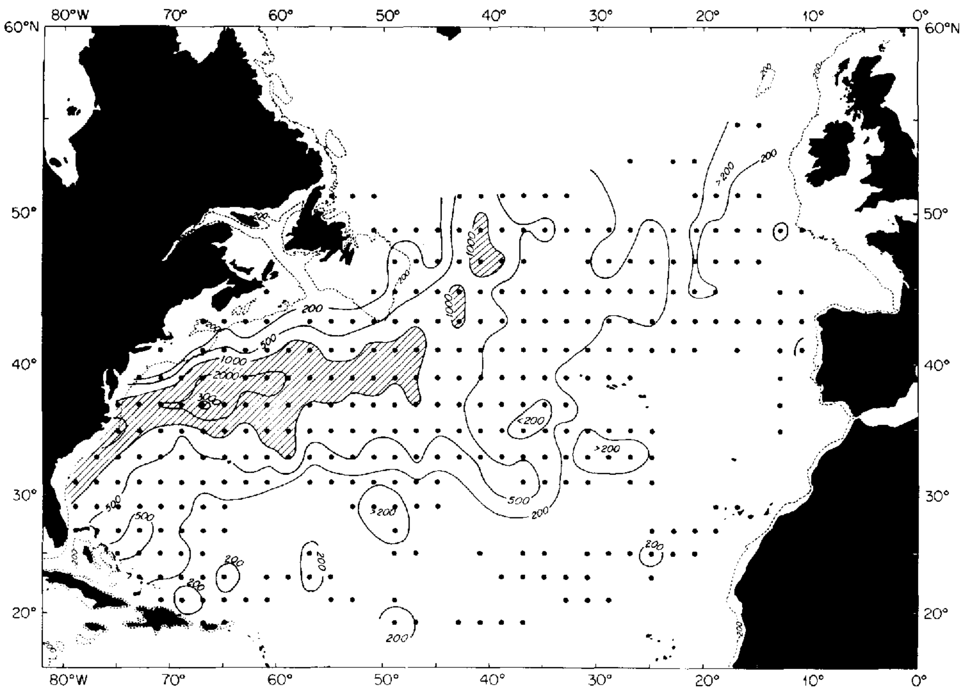

Figure 1. Surface eddy kinetic energy for the subtropical North Atlantic from Richardson (1983). Units are $cm^2\ s^{-2}$ and dots are where Richardson made his estimates. Figure is courtesy of P. L. Richardson.

The year-long, near-bottom record at 40°08′N, 62°24′W in Table 1 is now examined to see whether the presence of surface Gulf Stream meanders and rings, and abyssal velocity fluctuations of strength ~15 cm s^{-1} appear related. A value ~15 cm s^{-1} is consistent with the $KE_f = 142$ $cm^2\ s^{-2}$ value at this site (Fig. 2). The location is in some ways well suited for this examination. First, a strong (~10 cm/s), abyssal westward current passes the site (Richardson *et al.*, 1981; Weatherly and Kelley, 1982). Thus a strong "DC" signal (the abyssal westward current) can be examined to see if it is affected by a transitory signal (the presence of a Gulf Stream meander or ring overhead). Second, the site is at the base of the continental rise and less prone to "contamination" by topographic Rossby waves than a site further up the rise. Third, coverage of the surface position of the Gulf Stream is available for the period of interest (the NWS/NESS Oceanographic Analyses).

Figure 3 summarizes a test to see whether the deep flow changed markedly when a Gulf Stream meander or ring was overhead. Each daily averaged current vector was compared to the surface chart for the corresponding day (charts are issued three times weekly and each chart was assumed valid until updated by a new one). Three

Table 1. Listing of deep (depths ≳4000 m) eddy kinetic energy per unit mass (KE_f) for sites in the western North Atlantic determined from published records of duration ≳8 months. Those from Tarbell (1980), from Tarbell and Spencer (1978) and Tarbell *et al.* (1978) with duration >500 days are average values from different records weighted by their relative duration to the total duration. In two cases from Levy *et al.* (1982) simultaneous records from 4000 m and 4900 m depth were available; the deeper values are lsited. For comparison the mean kinetic energy per unit mass KE_m is also given.

Coordinates	Water depth (m)	Measurement depth (m)	Duration (days)	KE_f ($cm^2 s^{-2}$)	KE_m ($cm^2 s^{-2}$)	Reference
31°04′N, 72°24′W	~5220	4987	351	68	5	Mills and Rhines, 1979
37°40′N, 70°00′W	~4100	~4000	548	74	6	Luyten, 1977
37°00′N, 70°00′W	~4339	4138	241	88	9	Spencer *et al.*, 1979
36°40′N, 70°00′W	~4200	~4000	740	104	17	Luyten, 1977
36°30′N, 69°20′W	4468	4267	238	84	4	Spencer *et al.*, 1979
36°30′N, 70°00′W	4463	4262	239	57	10	Spencer *et al.*, 1979
35°59′N, 70°33′W	~4500	4000	565	65	4	Luyten, 1977
31°01′N, 69°29.9′W	5355	5330	445	36	4	Owens *et al.*, 1982
28°01′N, 69°40′W	5460	4000	719	14	2	Tarbell and Spencer, 1978
28°09′N, 68°40′W	5260	4000	520	8	2	Tarbell and Spencer, 1978
40°41′N, 63°02′W	4500	4490	248	78	2	Koenig *et al.*, 1983
40°08′N, 62°24′W	4950	~4940	364	142	6	Koenig *et al.*, 1983
39°53′N, 62°28′W	5000	4985	245	54	39	Koenig *et al.*, 1983
35°56′N, 59°02′W	5204	4009	604	70	12	Tarbell *et al.*, 1978
34°N, 60°W	~4700	~4000	264	18	34	Schmitz, 1976
32°59′N, 64°24′W	4527	4016	270	30	1	McKee *et al.*, 1981
32°52′N, 57°29′W	4620	4560	~240	18	232	Bird *et al.*, 1982
31°2′N, 60°4′W	5550	4018	215	6	0	Spencer *et al.*, 1979
41°29′N, 55°W	4768	3975	785	100	1	Tarbell *et al.*, 1978
40°30′N, 55°30′W	~5000	4000	513	134	11	Hendry, 1982
40°27′N, 55°02′W	5174	3998	783	131	15	Tarbell *et al.*, 1978

40°27′N, 55°00′W	5270	3993	783	123	11	Tarbell *et al.*, 1978
38°30′N, 54°56′W	5344	4005	781	123	14	Tarbell *et al.*, 1978
37°29′N, 55°00′W	5331	4006	779	105	26	Tarbell *et al.*, 1978
35°57′N, 55°30′W	5457	3997	235	116	30	Tarbell *et al.*, 1978
35°55′N, 55°05′W	5062	4001	522	106	57	Tarbell *et al.*, 1978
35°56′N, 54°46′W	5345	3978	747	99	92	Tarbell *et al.*, 1978
35°58′N, 53°46′W	5469	4000	657	76	8	Tarbell *et al.*, 1978
35°36′N, 55°05′W	5345	4013	776	88	56	Tarbell *et al.*, 1978
35°15′N, 55°00′W	5487	3998	257	73	6	Tarbell *et al.*, 1978
34°55′N, 55°04′W	5508	4023	520	69	1	Tarbell *et al.*, 1978
31°55′N, 54°59′W	5593	4014	762	10	1	Tarbell *et al.*, 1978
28°13′N, 54°57′W	5785	4000	239	4	0	Spencer *et al.*, 1979
16°41′N, 54°20′W	~5600	3946	354	20	3	Koblinsky *et al.*, 1979
15°02′N, 54°13′W	~5350	4038	353	9	2	Koblinsky *et al.*, 1979
15°23′N, 53°55′W	~5400	4020	355	8	0	Koblinsky *et al.*, 1979
15°12′N, 53°12′W	~5300	4008	353	8	0	Koblinsky *et al.*, 1979
38°52′N, 46°54′W	5332	4016	382	79	1	Levy *et al.*, 1982
38°41′N, 45°37′W	4994	4875	385	45	27	Levy *et al.*, 1982
39°46′N, 43°57′W	4695	4029	391	46	8	Levy *et al.*, 1982
38°58′N, 44°07′W	4960	4928	388	36	8	Levy *et al.*, 1982
39°40′N, 42°06′W	5009	4000	441	39	15	Levy *et al.*, 1982
38°30′N, 42°23′W	5091	4000	438	18	6	Levy *et al.*, 1982
37°00′N, 42°00′W	4788	4053	398	10	9	Levy *et al.*, 1982
28°01′N, 48°3′N	4954	4006	336	6	0	Tarbell, 1980
27°56′N, 48°52′N	5106	4016	334	5	1	Tarbell, 1980
27°51′N, 48°41′N	4881	3978	513	6	1	Tarbell, 1980
26°52′N, 49°14′N	4881	3883	333	6	0	Tarbell, 1980
27°26′N, 49°09′N	4268	4018	511	5	0	Tarbell, 1980
26°26′N, 41°13′N	4315	4015	342	7	1	Tarbell, 1980
27°14′N, 40°21′N	4723	3990	343	4	0	Tarbell, 1980

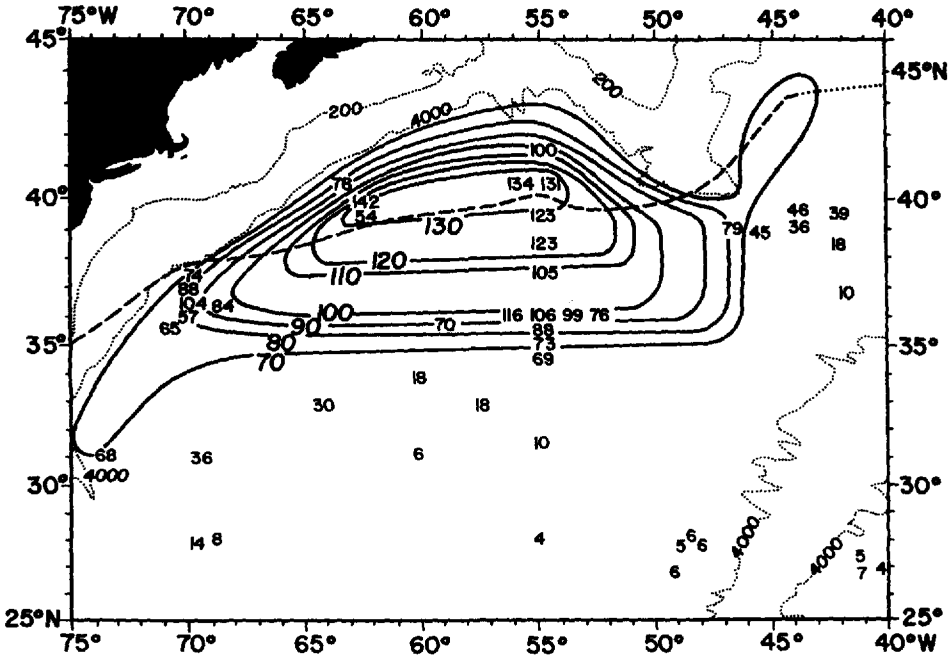

Figure 2. Deep fluctuating kinetic energy values (small numbers) and contours (large number) for the subtropical western North Atlantic. Units are $cm^2 s^{-2}$ and references for values are in Table 1. Selected 200 m and 4000 m isobaths are given (thin dotted lines). Dashed line is landward edge of the surface Gulf Stream as determined by Auer (1982). The values from the North Equatorial Current region (~ 15N, 49W) in Table 1 are not shown. These values are small and to expand this figure latitudinally 50% to include them seemed unwarranted.

classifications were chosen, and for each the frequency of occurrence of different flow directions and corresponding current strength was tabulated. Category 1 has the Gulf Stream meanders and rings well to the south (≥0.5° latitude) of the site. Presumedly, the deep flow is then westward and unaffected by Gulf Stream fluctuations. Category 2 is an intermediate one. Gulf Stream meanders and rings are still to the south but within 0.5° latitude of the site. The deep flow then is supposedly still westward, but because of uncertainties in Gulf Stream positioning (≈10 km accuracy of the method (Brown *et al.*, 1983) and intermittent cloud cover) as well as possible tilting away from the vertical with depth of meanders and rings, fewer instances of westward deep flow might be expected. Category 3 has a Gulf Stream meander or ring directly over the site. If a significant component of the surface fluctuations extends to the bottom and the KE_f value is due primarily to these fluctuations, deep flows ~15 cm s^{-1} in all directions might then be expected. The results for the three categories shown in Figure 3 agree with the above expectations. Thus, for Category 1 the flow was strongly and predominantly (98% of the time) to the west. For Category 2 the flow was strongly westward 80% of the time. In contrast, for Category 3 (meander or ring overhead)

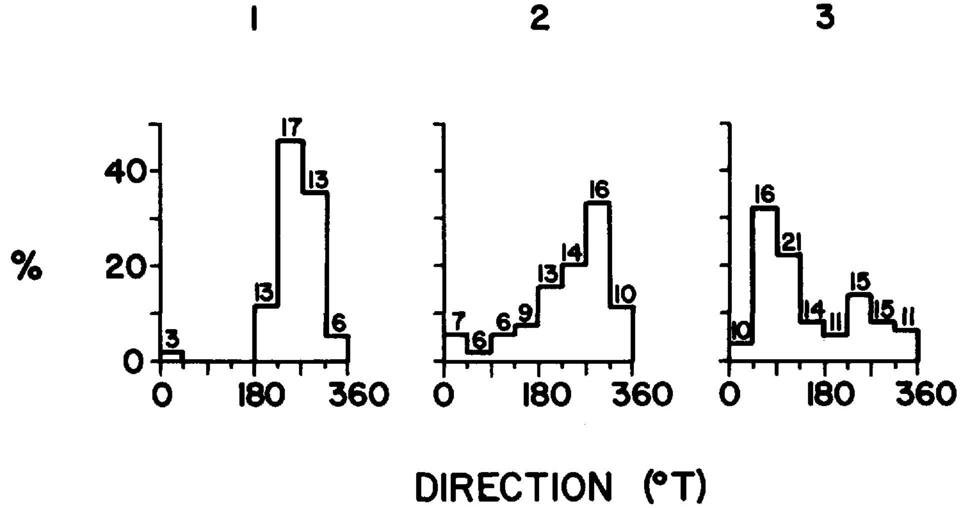

Figure 3. Histograms of frequency of flow direction occurrence for Categories 1, 2 and 3. 1 has Gulf Stream meanders and rings well to the south ($\gtrsim 0.5°$ latitude) of the site (40N, 62W); 2 has them south of the site but within 0.5° latitude; 3 has either a meander or ring over the site. Numbers above each octant are the mean speeds (cm s^{-1}). The fraction of time Categories 1, 2 and 3 occurred during the 364-day record are .27, .30, .43, respectively.

flows ~15 cm s^{-1} are recorded for each octant with westward flow occurring only 31% of the time. Thus, it appears that at this site the deep KE_f value is not inconsistent with it being due to Gulf Stream fluctuations extending to the bottom. This in turn suggests that the abyssal KE_f pattern in Figure 2 may be due to Gulf Stream fluctuations.

3. Bottom friction dissipation estimate

The net frictional dissipation per unit area throughout the turbulent bottom boundary layer $D = \boldsymbol{\tau}_o \cdot \mathbf{u}_b$ (Tennekes and Lumley, 1972), where $\boldsymbol{\tau}_o$ is the bottom stress and $\mathbf{u}_b$ the free-stream velocity just above the bottom layer. It is convenient to decompose $\boldsymbol{\tau}_o$ and $\mathbf{u}_b$ into components due to the mean (denoted by an overbar) and fluctuation (denoted by a prime) and to introduce the friction velocity $u_*^2 \equiv |\boldsymbol{\tau}_o|/\rho$, where ρ is the fluid density. The mean of D is then

$$\begin{aligned}\overline{D} &= \overline{\boldsymbol{\tau}}_o \cdot \overline{\mathbf{u}}_b + \overline{\boldsymbol{\tau}'_o \cdot \mathbf{u}'_b} \\ &= \rho\, \overline{u}_*^2 \overline{s}_b \cos \overline{\alpha} + \rho\, \overline{(u_*'^2 s'_b \cos \alpha')}\end{aligned} \qquad (1a)$$

where $\overline{\alpha}$ is the angle between $\overline{\boldsymbol{\tau}}_o$ and $\overline{\mathbf{u}}_b$, α' is the angle between $\boldsymbol{\tau}'_o$ and $\mathbf{u}'_b$, $\overline{s}_b \equiv |\overline{\mathbf{u}}_b|$ and $s'_b \equiv |\mathbf{u}'_b|$. Observations and theory (e.g., Weatherly, 1972; Koenig *et al.*, 1983) indicate that $\overline{\alpha}, \alpha' \lesssim 10°$. Thus $\cos \overline{\alpha} \simeq 1.0$ and $\cos \alpha' \simeq 1.0$ and (1) can be rewritten as

$$\overline{D} = \rho\, |\overline{u}_*^2 \overline{s}_b + \overline{u_*'^2 s'_b}|. \qquad (1b)$$

The friction velocity can be related to $\mathbf{u}_b$ by the geostrophic drag coefficient c_g which in turn weakly depends on $|\mathbf{u}_b|$, the bottom roughness z_o, and the coriolis parameter f (e.g., Weatherly, 1972), i.e.,

$$u_* = c_g\,(|\mathbf{u}_b|/fz_o)\,|\mathbf{u}_b|. \tag{2}$$

Since $s_b' \sim 3\,\bar{s}_b$, typically (Table 1), and c_g depends weakly on its argument (*ibid.*) c_g is taken to be the same constant for the mean and fluctuating parts of (1b), i.e.

$$\overline{D} = \rho c_g^2\,[\bar{s}_b^3 + \overline{s_b'^3}] \tag{1c}$$

Eq. (1c) is the basis for the calculations presented below. It will be used to estimate the bottom frictional dissipation within the $KE_f = 70\ \mathrm{cm^2\,s^{-2}}$ contour of Figure 2. Two aspects of it warrant discussion. The first deals with the appropriateness of using (1c) to make such an estimate within this contour. The region within the $KE_f = 70\ \mathrm{cm^2\,s^{-2}}$ contour consists basically of portions of the Sohm and Hatteras Abyssal Plains and the lower continental rise. Irregular features such as the New England and Corner Rise Seamounts comprise a relatively small fraction of the total area of concern. Because the bottom where the calculation is made is generally so featureless and regular, as opposed to one typical of a mid-ocean ridge system, it does not seem inappropriate to use (1c) to estimate $\overline{D}$. The second aspect deals with the term $\overline{s_b'^3}$ in (1c). The contribution to $\overline{D}$ due to the fluctuations depends on the third moment of s_b'. From the references in Table 1 what can be found or inferred is $KE_m \equiv \frac{1}{2}\bar{s}_b^2$ (KE_m is the mean kinetic energy per unit mass) and $KE_f \equiv \frac{1}{2}\overline{s_b'^2}$ (here it is temporarily assumed that KE_m and KE_f do not change appreciably from 4 km depth to just above the bottom boundary layer). While $\bar{s}_b^3 = (2KE_m)^{3/2}$, $\overline{s_b'^3} \neq (2KE_f)^{3/2}$ in general. In the references of Table 1, $\overline{s_b'^3}$ is not given. Thus there is the practical problem of estimating $\overline{s_b'^3}$ from KE_f values. How it is done here is discussed shortly. Independent of how s_b' is estimated, since it is a positive quantity, regions of large KE_f are also regions of large $\overline{s_b'^3}$, and the contoured KE_f region of Figure 2 is also a region of relatively high eddy bottom dissipation.

While it seems that the KE_f distribution sketched in Figure 2 is due to the Gulf Stream, it is not clear when the larger KE_m values in Table 1 are due to it or a deep western boundary current. Since the intent is to estimate bottom dissipation for the Gulf Stream System, only the following is estimated here

$$\overline{D}_f \equiv \rho c_g^2\,\overline{s_b'^3}, \tag{3}$$

i.e., the contribution to (1c) due to the fluctuations. Since KE_f is typically about an order of magnitude larger than KE_m (Table 1) the areal average of $\overline{D}$ should be nearly that of $\overline{D}_f$.

The references in Table 1 provide information on the second moment of s_b' rather than the needed third moment found in (3). To compute $\overline{s_b'^3}$ from the current meter records would be a straightforward task. However, a large number of records obtained by many investigators (see the references in Table 1) would be involved and the process

Table 2. Values of the geostrophic drag coefficient $c_g = u_*/|\mathbf{u}_b|$ for various deep water sites. The last entry was inferred using methods discussed in Weatherly and Wimbush (1980) from data shown in Bird *et al.* (1982) when the mean bottom currents $|\mathbf{u}_b| \lesssim 25$ cm s^{-1}. When 25 cm s$^{-1} \lesssim |\mathbf{u}_b| \lesssim 40$ cm s^{-1} the inferred c_g ranged from ~.04 to ~.08; however, we have little confidence in these larger c_g values and do not enter them. At larger $\mathbf{u}_b$ considerable sediment erosion occurs in the region (Weatherly and Kelley, 1982) and the technique used to determine u_* becomes suspect (e.g., Adams and Weatherly, 1981).

Region	Water depths	c_g	Reference
Eastern North Pacific 32N, 120W	2–4 km	.045	Wimbush and Munk (1970)
Florida Straits 25°44′N, 79°28′W	780 m	.038	Weatherly (1972)
Blake Bahama Outer Ridge 28°22′N, 74°13′	4750 m	.045	Weatherly and Wimbush (1980)
Bermuda Rise 32°52′N, 57°29′W	4620 m	.035	Bird *et al.* (1982)
Scotian Rise 40°06′N, 62°29′W	4900 m	~.04	Inferred from data in Bird *et al.* (1982) when $|\mathbf{u}_b| \lesssim 25$ cm s^{-1}.

would probably be a lengthy one. The approach here is to try to estimate $\overline{s_b'^3}$ from KE_f. The actual $\overline{s_b'^3}$ calculations are deferred to a future study. It is estimated by

$$\overline{s_b'^3} = A\,(2\,KE_f)^{3/2}, \tag{4}$$

where A is constant.

The discussion below is limited to the region of interest (within the $KE_f = 70$ cm^2/s^2 contour in Figure 2 where the dissipation estimate is made). The subsequent remarks about skewness apply only to records whose reference in Table 2 is a technical report since this information is given only in the reports. The latter is not a serious restriction since 80% is from reports.

The skewness of the vector speeds s_b is given and in all cases it is positive. If s_b is positively skewed so is s_b'; hence $A > 1$. The three entries in Table 1 from Koenig *et al.* (1983) (near 40N, 62W) were obtained by the author. The computed A for each ranges from 1.5 to 5.0 with a record duration weighted average of 2.6. The s_b skewness range of these records is similar to those of the other records. Here $A = 2.6$ is taken to be a representative value to use for estimating $\overline{s'^3}$ via (4).

A value of c_g is now selected. Table 2 lists c_g determined at various ocean sites. They range from .035 to .045. A representation value is taken to be $c_g = .040$.

Table 3 summarizes the dissipation calculations made using (3) and (4), with $A = 2.6$ and $c_g = .040$. The total energy dissipation by bottom friction associated with fluctuations within the $KE_f = 70$ cm^2 s^{-2} contour is 2.2×10^{17} ergs s^{-1}. For comparison Fofonoff (1981) calculated that $\approx 2 \times 10^{17}$ ergs s^{-1} is the rate of energy input by the

Table 3. Estimate of area (II), $\overline{s'^3}$ (V), and dissipation (VI) between indicated KE_f contour or contours in Figure 2. Total area and dissipation within KE_f = 70 $cm^2\ s^{-2}$ contour given at bottom of columns II and VI, respectively.

I	II	III	IV	V	VI	VII
Strip	Area ($cm^2 \times 10^{15}$)	Bounding KE_f Isopleth or Isopleths ($cm^2\ s^{-2}$)	Representative KE_f ($cm^2\ s^{-2}$)	$A(2{*}IV)^{3/2}$ ($cm^3\ s^{-1} \times 10^3$)	$\rho c_g{}^2{*}V{*}II$ ($ergs\ s^{-1} \times 10^{16}$)	Relative contribution (%)
1	5.33	70,80	75	4.78	4.07	19
2	2.20	80,90	85	5.70	2.03	9
3	2.48	90,100	95	6.81	2.70	13
4	3.53	100,110	105	7.91	4.67	21
5	1.37	110,120	115	9.07	1.99	9
6	2.49	120,130	125	10.28	4.09	19
7	1.23	130	132	11.15	2.19	10
	18.53				21.55	

winds to the Gulf Stream System. The estimate made here indicates that bottom friction may be the dissipative mechanism for this gyre.

4. Summary and discussion

The estimate made here of bottom friction dissipation due to fluctuations of the Gulf Stream System of 2.2×10^{17} ergs s^{-1} essentially balances the estimate of work done by the wind stress over this system of $\approx 2 \times 10^{17}$ ergs s^{-1} by Fofonoff (1981). Letting c_g range from .035 to .045 (see Table 2) keeping A fixed results in the value varying from $(1.6 \text{ to } 2.7) \times 10^{17}$ ergs s^{-1}. However, a greater uncertainty in the estimate arises from choosing A for (4). Obviously, it is preferable to calculate $\overline{s_b'^3}$ directly than to use (4). Nonetheless, since s_b is positively skewed, $A > 1$. Thus, taking $c_g = 0.35$ and $A = 1$ gives a lower bound estimate of 0.6×10^{17} ergs s^{-1}. Hence, it seems reasonable to infer, accepting Fofonoff's input value of 2×10^{17} ergs s^{-1}, that over 30%, and probably somewhere between 50 and 100%, of the energy dissipation of the Gulf Stream System is due to bottom friction acting on Gulf Stream meanders and rings.

Three things could be done, other than the previously noted direct calculation of $\overline{s_b'^3}$, which would lead to a more precise estimate of bottom frictional dissipation. One is to acquire deep, long-term current meter observation about the Gulf Stream in the regions where little if any data exist e.g., between 47W and 55W, and between 55W and 70W (cf. Fig. 2). The second is to determine whether $\overline{s'^3}$ changes appreciably between 4000 m depth and the top of the bottom boundary layer. Over the Hatteras and Sohm Abyssal Plains that may not be true, but this needs confirmation particularly in light of bottom intensification of KE_f for a comparable region of the western

North Pacific reported by Schmitz *et al.* (1982). However, on the continental rise (Luyten, 1977) and on the southern flank of the Newfoundland Ridge (Levy *et al.*, 1982) KE_f increasing with depth in the lowest 1000 m occurs. This effect appears to be significant in that KE_f values within 200 m of the bottom were about 20% to 60% larger than those 1000 m above the bottom (*loc. cit.*). Thus $\overline{s_b'^3}$ inferred from data obtained from 1000 m above bottom on the continental rise may yield underestimates of bottom dissipation there. The third is to obtain more estimates of c_g, the geostrophic drag coefficient, for the region of interest. Only one of the values listed in Table 2 is from this region.

The total area within the $KE_f = 70 \text{ cm}^2 \text{ s}^{-2}$ contour in Figure 2 $\approx 2 \times 10^{16} \text{ cm}^2$. This is about 20% of the $\approx 1 \times 10^{17} \text{ cm}^2$ area of the Gulf Stream System (Fofonoff, 1981). Thus while bottom frictional dissipation is a major factor in the overall energy budget, it occurs in essentially a relatively small region of this gyre.

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