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# A Vertical Section of Eddy Kinetic Energy Through the Gulf Stream System

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Ocean current observations made by drifting buoys, SOFAR floats, and current meters are combined to produce the first section of eddy kinetic energy through the Gulf Stream and subtropical gyre along 55°W. Eddy kinetic energy peaks at 2000 $cm^2\ s^{-2}$ in the surface Gulf Stream near 39°N and decreases latitudinally and vertically to a low of 0.5 $cm^2\ s^{-2}$ in the abyssal gyre interior (4000 m, 28°N). Still further south, eddy energy increases slightly in the region of the North Equatorial Current.

## INTRODUCTION

Within the past 5 years, surface drifting buoys and neutrally buoyant SOFAR floats have provided new data to determine the eddy kinetic energy in the vicinity of the Gulf Stream. When these new buoy and float data are combined with existing current meter data, we are able to map for the first time the geographical distribution of eddy kinetic energy within the Gulf Stream and subtropical gyre. Eddy kinetic energy exceeds the energy of the mean flow and has implications concerning ocean dynamics and eddy mixing.

Earlier attempts to describe the variation of eddy kinetic energy near the Gulf Stream were based on (1) surface ship drift observations [*Wyrtki et al.*, 1976] and (2) moored current meter observations [*Luyten*, 1977; *Schmitz*, 1978, 1980]. The ship drift observations are suspect because of their spatial averaging and large errors. The current meter observations do not provide a complete picture since they could not be obtained within the most energetic regions of the Stream. Recently, *Schmitz et al.* [1981] described the first few SOFAR floats tracked in and near the Gulf Stream and concluded that the eddy kinetic energy based on float data was compatible with values from moored current meters to the extent the data were comparable. The work presented here is an extension of this, using a larger set of floats and a new set of surface drifters; it combines these Lagrangian data with those from moored current meters.

## DATA AND METHODS

Thirty drifting buoys, tracked by satellite over a 5-year period, provided near-surface velocity measurements. While near the Gulf Stream and in isolated eddies, buoys closely followed geostrophic currents. In regions of low eddy energy, the buoys' velocities could have been influenced by local winds and waves acting on their hulls. A description of some of the buoy trajectories in and near the Gulf Stream has been given by *Richardson* [1980, 1981]; a statistical summary of 110 trajectories in the North Atlantic is given by *Richardson* [1982].

Seventeen SOFAR floats, tracked acoustically over 15 months by a moored array of listening stations, provided subsurface velocity data. A description of the trajectories during the first 5 months was given by *Richardson et al.* [1981], and a description of the trajectories from the total 15 months is in preparation by W. B. Owens. Presently more float data are being obtained near the Gulf Stream, and these will be used to refine our estimates of ocean variability.

Buoy and float trajectories were low pass filtered to reduce position errors and inertial and tidal fluctuations. Velocity values were then computed at even time increments along each trajectory and grouped into geographical boxes (Table 1, Figures 1, 2). For each box, the mean velocity $\bar{u}$, $\bar{v}$ in the $x$ and $y$ directions and the departures $u'$, $v'$ from the mean were computed. Eddy kinetic energy values per unit mass were calculated by using EKE $= 0.5(\overline{u'^2} + \overline{v'^2})$.

Values of eddy kinetic energy measured by current meters were obtained from several sources [*Schmitz,* 1978, 1980; *Koblinsky et al.*, 1979; *Fu et al.*, 1982; *Hendry*, 1982; *Dickson*, 1983]. Most records were a year or longer in duration. Several, near the Gulf Stream, were over 2 years long. The shortest was 233 days. A few records were omitted because they were biased by a large event or local topography. Nine-month subsets of 27 month current meter records taken under the Stream produced eddy energy values that vary by nearly 50% from the 27 month mean (W. J. Schmitz, Jr., personal communication, 1982). In general, this unsteadiness has a small effect because geographical variations dominate.

## RESULTS

When the values of eddy kinetic energy from buoys, floats, and current meters are combined and contoured, a remarkably clear and consistent picture emerges (Figure 3). This is the first contoured vertical section of eddy kinetic energy that has been made. Along 55°W, which cuts through the central region of the subtropical gyre, eddy kinetic energy per unit mass peaks at 2000 $cm^2\ s^{-2}$ in the surface Gulf Stream jet near 39°N. Eddy energy decreases vertically and latitudinally to a low of 0.5 $cm^2\ s^{-2}$ in the abyssal gyre interior (4000 m, 28°N). Eddy energy diminishes from the surface Gulf Stream maximum over relatively short space scales; an $e$ folding occurs at about 300 km horizontally and 500 m in depth. Overall, eddy energy varies by a factor of 4000.

Above 1000 m, eddy energy increases vertically toward the sea surface and horizontally toward the Gulf Stream axis. Values at the sea surface are 200 $cm^2\ s^{-2}$ in the gyre interior increasing to 2000 $cm^2\ s^{-2}$ at the Stream's axis. Below 1000 m, eddy energy is nearly uniform vertically. The dominant variation in eddy energy is a latitudinal increase from a low of 0.5 $cm^2\ s^{-2}$ in the gyre interior to a high of 140



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TABLE 1. Summary of SOFAR Float and Surface Drifter Data

| Center Latitude (°N) | Eddy Kinetic Energy ($cm^2 s^{-2}$) | Number of Semi-Daily Observations |
|---|---|---|
| | *Surface Drifters* | |
| 45.5 | 160 | 33 |
| 44.5 | 220 | 69 |
| 43.5 | 280 | 220 |
| 42.5 | 410 | 374 |
| 41.5 | 640 | 620 |
| 40.5 | 1350 | 758 |
| 39.5 | 1960 | 649 |
| 38.5 | 1590 | 565 |
| 37.5 | 1210 | 452 |
| 36.5 | 920 | 459 |
| 35.5 | 720 | 363 |
| 34.5 | 790 | 350 |
| 33.5 | 630 | 234 |
| 32.5 | 190 | 200 |
| 31.5 | 120 | 143 |
| 30.5 | 120 | 88 |
| 29.5 | 290 | 72 |
| 28.5 | — | 5 |
| 27.5 | — | 2 |
| 26.5 | — | 0 |
| 25.5 | — | 7 |
| 24.5 | 230 | 65 |
| 23.5 | 230 | 88 |
| 22.5 | 180 | 95 |
| 21.5 | 130 | 49 |
| 20.5 | 140 | 42 |
| **Center Latitude (°N)** | **Eddy Kinetic Energy ($cm^2 s^{-2}$)** | **Number of Daily Observations** |
| | *SOFAR Floats: 700 m Floats* | |
| 45 | 17 | 109 |
| 43 | 31 | 86 |
| 41 | 140 | 139 |
| 39 | 250 | 122 |
| 37 | 200 | 107 |
| 35 | 120 | 134 |
| 33 | 41 | 109 |
| 31 | 22 | 141 |
| 29 | — | 0 |
| 27 | 18 | 80 |
| 25 | — | 9 |
| 23 | 24 | 189 |
| | *2000 m Floats* | |
| 43 | 15 | 223 |
| 41 | 70 | 214 |
| 39 | 140 | 291 |
| 37 | 60 | 241 |
| 35 | 34 | 403 |
| 33 | 11 | 602 |
| 31 | — | 19 |
| 29 | 2.8 | 136 |
| 27 | 2.1 | 306 |
| 25 | 1.4 | 113 |

Individual velocity values were grouped into boxes 10° in longitude and 2° in latitude for floats and 1° in latitude for buoys. Two floats and two buoys that were trapped for long periods of time in energetic eddies were not used. The minimum in surface eddy kinetic energy near 31°N appears to be due to a particularly slow buoy which stayed in this region for a long time plus the low number of velocity observations there.

$cm^2 s^{-2}$ under the Stream's axis near 39°N. North of 30°N, eddy energy has a weak minimum near depths of 1500–2000 m. Below this level, values increase slightly to a secondary peak at abyssal depths (~4000 m). South of the central gyre region, eddy energy values increase in the North Equatorial Current, reaching a weak maximum near 15°N.

The peak value of 2000 $cm^2 s^{-2}$ lies in a narrow band of high eddy energy which follows the Gulf Stream eastward, decreasing from a maximum of 3000 $cm^2 s^{-2}$ located near 37°N, 67°W [*Richardson*, 1982]. At abyssal depths, values under the Stream along 55°W are about 50% greater than those under the Stream at 70°W [*Luyten*, 1977; *Schmitz*, 1977]. The minimum value of 0.5 $cm^2 s^{-2}$ at 4000 m is typical of a broad region of low eddy energy ~1 $cm^2 s^{-2}$ that is located between 20° and 30°N and that extends eastward from 65°W across the mid-Atlantic ridge and northward into the Northeastern Atlantic [*Dickson*, 1983].

## DISCUSSION

Most of the area in the eddy kinetic energy section (Figure 3) contains relatively low eddy energy values <50 $cm^2 s^{-2}$. The high eddy energy region is small and clearly associated with the Gulf Stream. These results strongly suggest that the major source of eddy energy in the western North Atlantic is the meandering Gulf Stream jet. Energy appears to be transmitted both latitudinally and vertically away from the Gulf Stream. In the high energy region near the Gulf Stream, one expects eddy fluxes of momentum, vorticity, and heat to be maximum, and strong eddy-mean flow interactions most probable. It is in this region that eddies are thought to drive the Gulf Stream recirculation (near 36°N, Figure 1) in both upper and abyssal layers [*Schmitz*, 1980; *Holland et al.*, 1983].

In the low eddy kinetic energy region, wind-forced currents have been identified, but they are not dominant. At 15°N, which is in the Trade Wind Zone, approximately 10–15% of the total eddy kinetic energy is generated by wind forcing (C. J. Koblinsky, personal communication, 1982). In the frequency band with periods from 4 to 40 days, wind-forced motions account for 26% of the eddy energy at 500 m and 39% at 4000 m [*Koblinsky and Niiler*, 1982]. In the low energy mid-gyre region it is possible that wind-forced motions could account for a larger percentage of the eddy energy.

The dispersion of SOFAR floats at several locations within the subtropical gyre suggests that eddy horizontal mixing is approximately proportional to eddy kinetic energy [*Price*, 1983]. Therefore, horizontal mixing is strongly inhomogeneous and may have a distribution much like that shown in Figure 3. Such large variations in horizontal mixing could strongly influence the distribution of ocean tracers [*Armi*, 1979; *Armi and Haidvogel*, 1982]. Hence, realistic models of ocean mixing should include these variations in the rate of eddy mixing. The one-dimensional steady advection-diffusion equation for a nonhomogeneous medium can be written

$$\left(V - \frac{\partial K}{\partial y}\right)\frac{\partial C}{\partial y} = K\frac{\partial^2 C}{\partial y^2}$$

where $V$ is the mean velocity in the northward direction $y$, $K$ is the eddy diffusivity, and $C$ is the concentration of passive ocean tracer [see *Armi and Haidvogel*, 1982]. The $\partial K/\partial y$ in the first term acts on the distribution of an ocean tracer like a mean velocity directed away from the Gulf Stream axis, from high to low eddy diffusivity. If the coefficient of

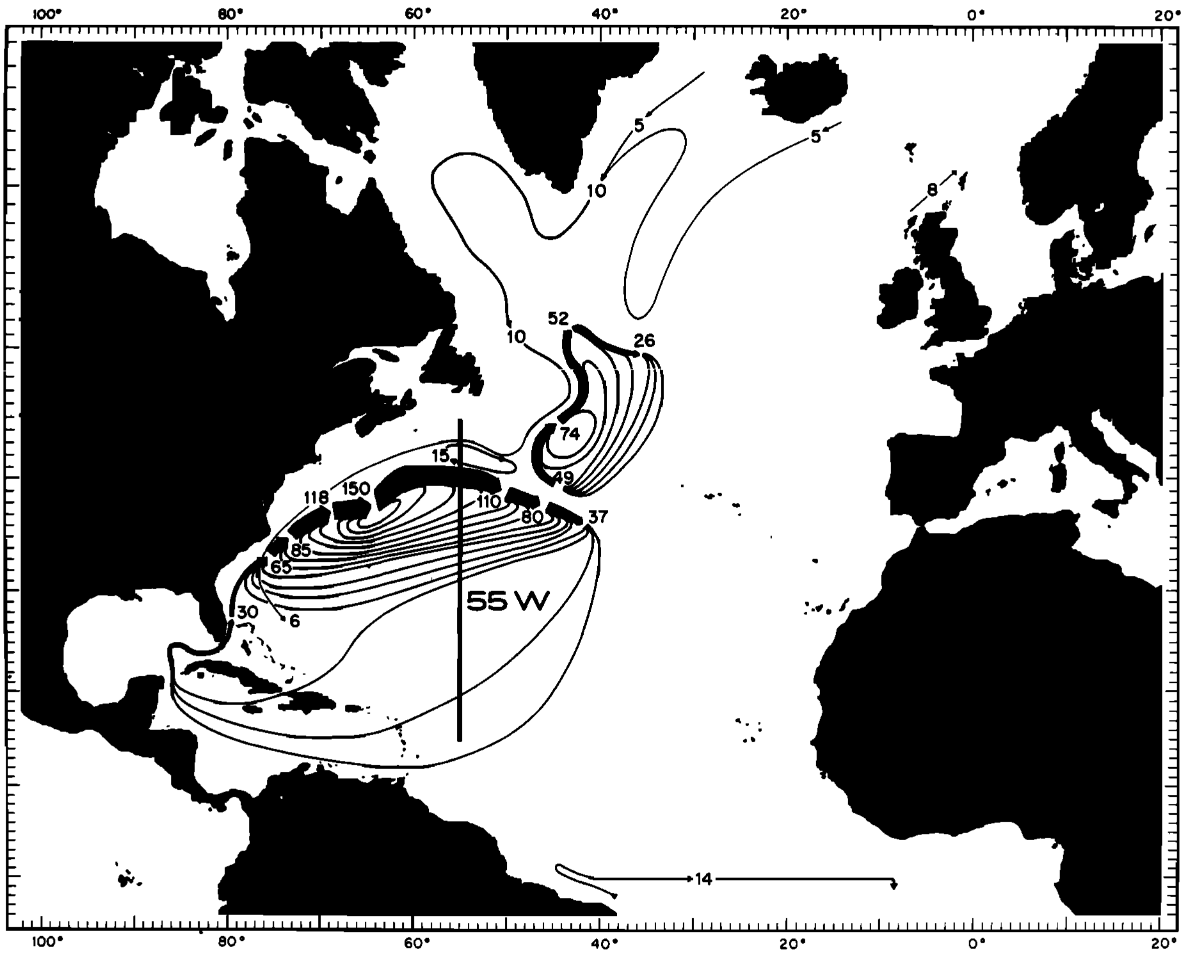


Fig. 1. Location of vertical section along 55°W superimposed on a map of the Gulf Stream system drawn by *Worthington* [1976]. Numbers refer to volume transport in units of $10^6$ $m^3$ $s^{-1}$.

horizontal eddy diffusion $K \sim 5 \times 10^7$ $cm^2$ $s^{-1}$ in the Gulf Stream and the $e$ folding length of eddy kinetic energy is ~300 km latitudinally, then $(\partial K/\partial y) \sim 2$ cm $s^{-1}$. Thus the magnitude of the latitudinal variation of diffusivity $\partial K/\partial y$ inferred from Figure 3 is the same approximate size as the characteristic mean velocity within the gyre.

## SUMMARY

SOFAR float and surface drifter velocity measurements located near 55°W were used to determine the geographical distribution of eddy kinetic energy in and near the Gulf Stream. The eddy energy values calculated from floats are remarkably consistent with some adjacent values calculated from moored current meters. The float, drifter, and current meter data were combined to contour a vertical section of eddy kinetic energy that extends through the Gulf Stream, the subtropical gyre and into the North Equatorial Current. The section shows quantitatively the peak of eddy energy (2000 $cm^2$ $s^{-2}$) associated with the surface Gulf Stream jet and the rapid decrease of eddy energy away from this peak. The $e$ folding occurs at about 300 km latitudinally and 500 m vertically. Low values of eddy energy, ranging from 0.5 to 5 $cm^2$ $s^{-2}$, are found to be characteristic of the abyssal gyre interior from 15 to 30°N.

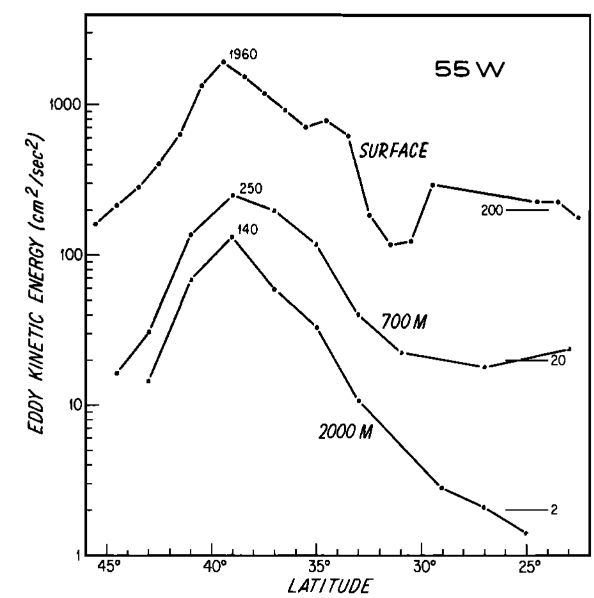


Fig. 2. Profiles of eddy kinetic energy (per unit mass) along 55°W from freely drifting satellite tracked buoys and neutrally buoyant SOFAR floats. The peak value of eddy energy ~2000 $cm^2$ $s^{-2}$ coincides with a peak in mean velocity in the Gulf Stream.

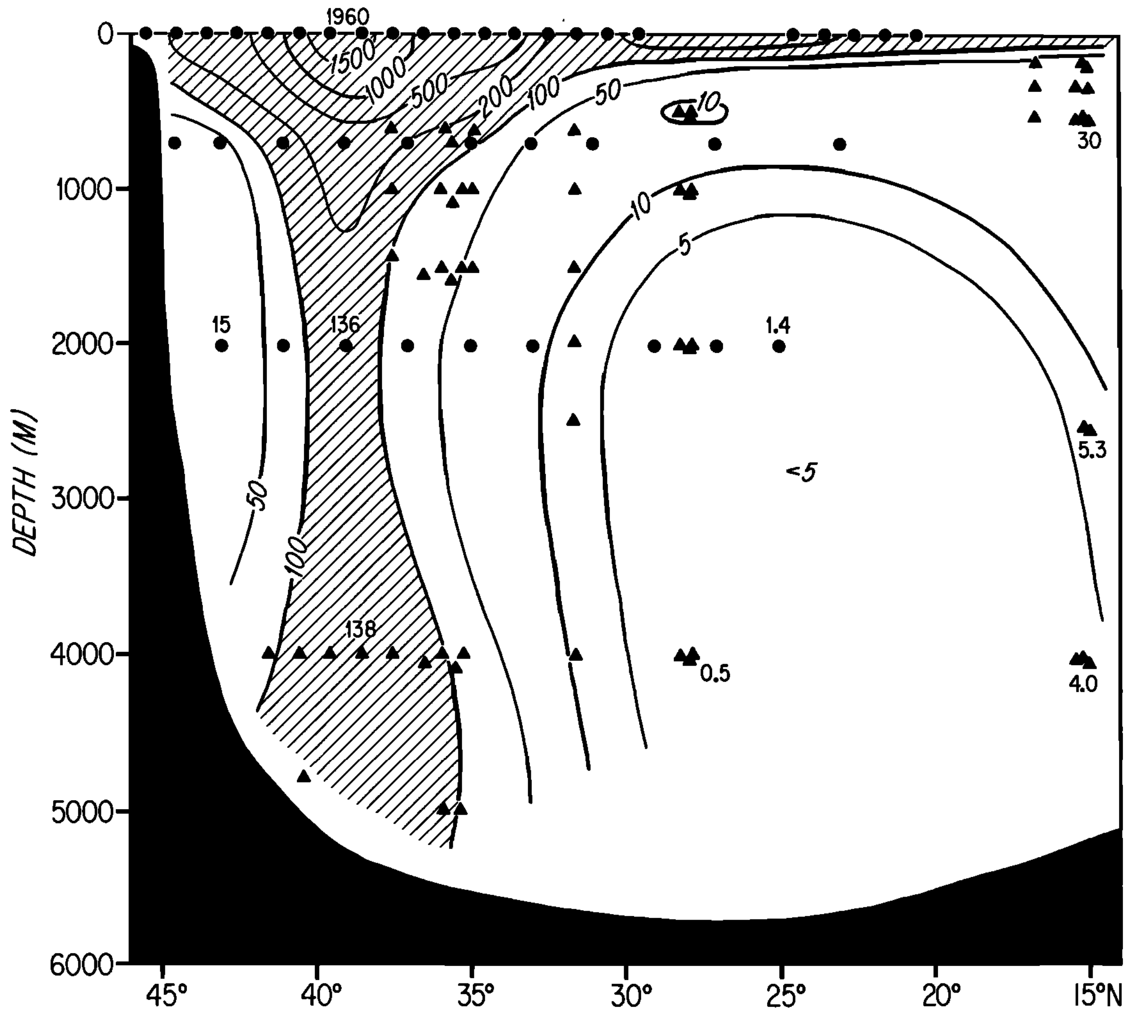


Fig. 3. Vertical section along 55°W showing eddy kinetic energy within the Gulf Stream and subtropical gyre. Triangles show current meter locations, and dots show centers of boxes into which drifting buoy and SOFAR float data were grouped. Eddy energy (per unit mass) peaks to 2000 $cm^2\ s^{-2}$ in the near surface Gulf Stream jet and decreases latitudinally and vertically to a low of 0.5 $cm^2\ s^{-2}$ in the abyssal gyre interior (4000 m, 28°N).

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