Velocity and Eddy Kinetic Energy of the Gulf Stream System from 700-m SOFAR Floats Subsampled to Simulate Pop-up Floats

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ABSTRACT

Velocity and eddy kinetic energy were calculated from SOFAR (sound fixing and ranging) float trajectories using original daily values and values subsampled at intervals of 15, 30, and 60 days to simulate pop-up floats that surface for position fixing at these time intervals. The mean velocity is well reproduced by the 15-day subsampled data. With the 30-day data, the peak velocity in the Gulf Stream is reduced, and its width is increased substantially. With the 60-day data, the Gulf Stream is highly modified, and its southern flanking countercurrent is no longer resolved. Calculated eddy kinetic energy is strongly diminished by subsampling; peak energy in the Gulf Stream of 710 $cm^2 s^{-2}$ using daily values is reduced to 64 $cm^2 s^{-2}$ using 60-day data. Calculated energy in the Sargasso Sea near 25°N, 60°W is reduced from 20 to 8 $cm^2 s^{-2}$. The larger percent decrease of calculated energy in the vicinity of the Gulf Stream, 30°–40°N, is due to energetic higher-frequency eddy motion in this area.

1. Introduction

A pop-up freely drifting subsurface float called ALACE (autonomous Lagrangian circulation explorer) was recently developed by R. Davis (Scripps Institution of Oceanography) and D. Webb (Webb Research Corporation) and is now being used in the Southern Ocean (Davis et al. 1992). This float drifts at a preselected depth, periodically pops up to the ocean surface, and is located by the Argos satellite system. Power is available for approximately 50 surfacings over a projected lifetime of 5 years. Subsurface trajectories and velocities are inferred from the periodic surfacings, which can be at intervals of a few days to several months.

This paper investigates the effect of the relatively infrequent recording of positions of pop-up floats on calculated and mapped velocity and eddy kinetic energy (EKE) distributions. Continuous SOFAR (sound fixing and ranging) float trajectories from the Gulf Stream region were subsampled at intervals of 15, 30, and 60 days, and velocity statistics were calculated by grouping observations into geographical boxes. Results are a simple graphical demonstration of how the picture of the Gulf Stream, developed using data sampled at 1-day intervals, is modified by subsampling. The results provide some guidance in planning future deployments of pop-up floats and in interpreting results from them in areas where there are no continuous float trajectories. It should be noted that the Gulf Stream's narrow and swift current and high eddy energy tends to emphasize the shortcomings of subsampling; these shortcomings would be less noticeable in broader, less energetic currents.

2. Data and methods

The data are a collection of SOFAR float trajectories from the northwestern Atlantic from a depth near 700 m, the level of highest data density and best geographical coverage. Approximately 26 000 float days of data from 1976 to 1985 were used (Fig. 1). These trajectories were obtained during several experiments, including POLYMODE (Spain et al. 1980; O'Gara et al. 1982), the Gulf Stream Recirculation Experiment (GUSREX) (Kennelly and McKee 1984; Wooding et al. 1989), and SITE L (34°N, 70°W) (Price et al. 1987). A summary of these data and their statistics is described by Owens (1991), as well as the less well-sampled deeper layers, 1300 and 2000 m.

The float data consist of time series of daily positions and velocity, pressure, and temperature values. Trajectories were subsampled at intervals of 15, 30, and 60 days, and the velocity between each two new positions was calculated. Each velocity calculated this way is a space and time average along the trajectory. To make the new series similar in form to the original ones, new daily positions and velocities were linearly

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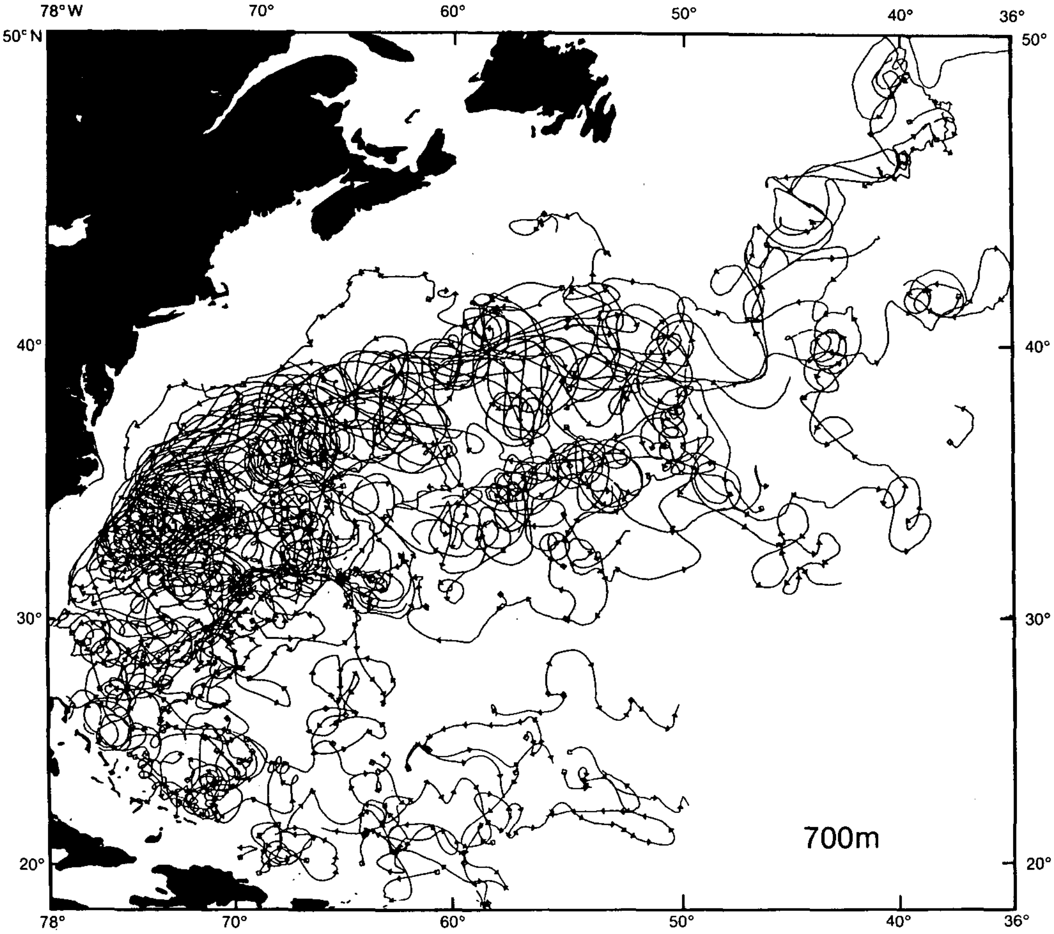

FIG. 1. Summary of SOFAR float trajectories near a depth of 700 db in the northwestern Atlantic. Data consist of 71 float years from 1976 to 1985.

interpolated between subsampled points. For example, 15 identical velocity values were spaced at 1-day intervals for each pair of 15-day subsampled positions. This was done to obtain horizontal distributions of velocity that could be grouped for further calculations. Some data at the end of each float trajectory were lost due to subsampling, the amount lost is roughly proportional to the sampling interval.

Velocity values were grouped into various boxes, and the average velocity and EKE were calculated. The EKE is the average of velocity variance about the mean velocity in the x and y directions. Values were calculated in 2° latitude × 5° longitude boxes for the whole region and in 1° × 10° boxes bounded by 60°–70°W to produce profiles through the Gulf Stream. On average, boxes contained 400 daily observations. Only boxes containing more than about 80 observations, or around 10 degrees of freedom, were retained for mapping. The number of degrees of freedom is equal to the number of 10-day intervals for which float data were available. Ten days is the estimated integral time scale of the Lagrangian autocorrelation function. The standard error of velocity was calculated from $(2 \times \text{velocity variance/degrees of freedom})^{1/2}$

The 2° × 5° and 1° × 10° box sizes are a trade-off between being large enough to contain enough velocity values so that statistically significant mean velocities can be calculated and being small enough to resolve the size and shape of the Gulf Stream and its recirculation. The boxes chosen here do resolve the Gulf Stream, but the errors of the mean are large, especially south of the Gulf Stream. Either more data or larger boxes are required to reduce the size of the errors.

The picture of the mean Gulf Stream determined from daily float data grouped into bins is assumed to be a correct picture of the mean Gulf Stream. The real mean Gulf Stream is probably smoother than the calculated mean due to an insufficient amount of float data. This problem is noticeable in box averages of velocity that appear noisy. Thus, we should be cautious in comparing pictures from subsampled data with an incorrect standard. Perhaps model simulations in which the mean fields are well known and model floats that could be cheaply and easily deployed would prove

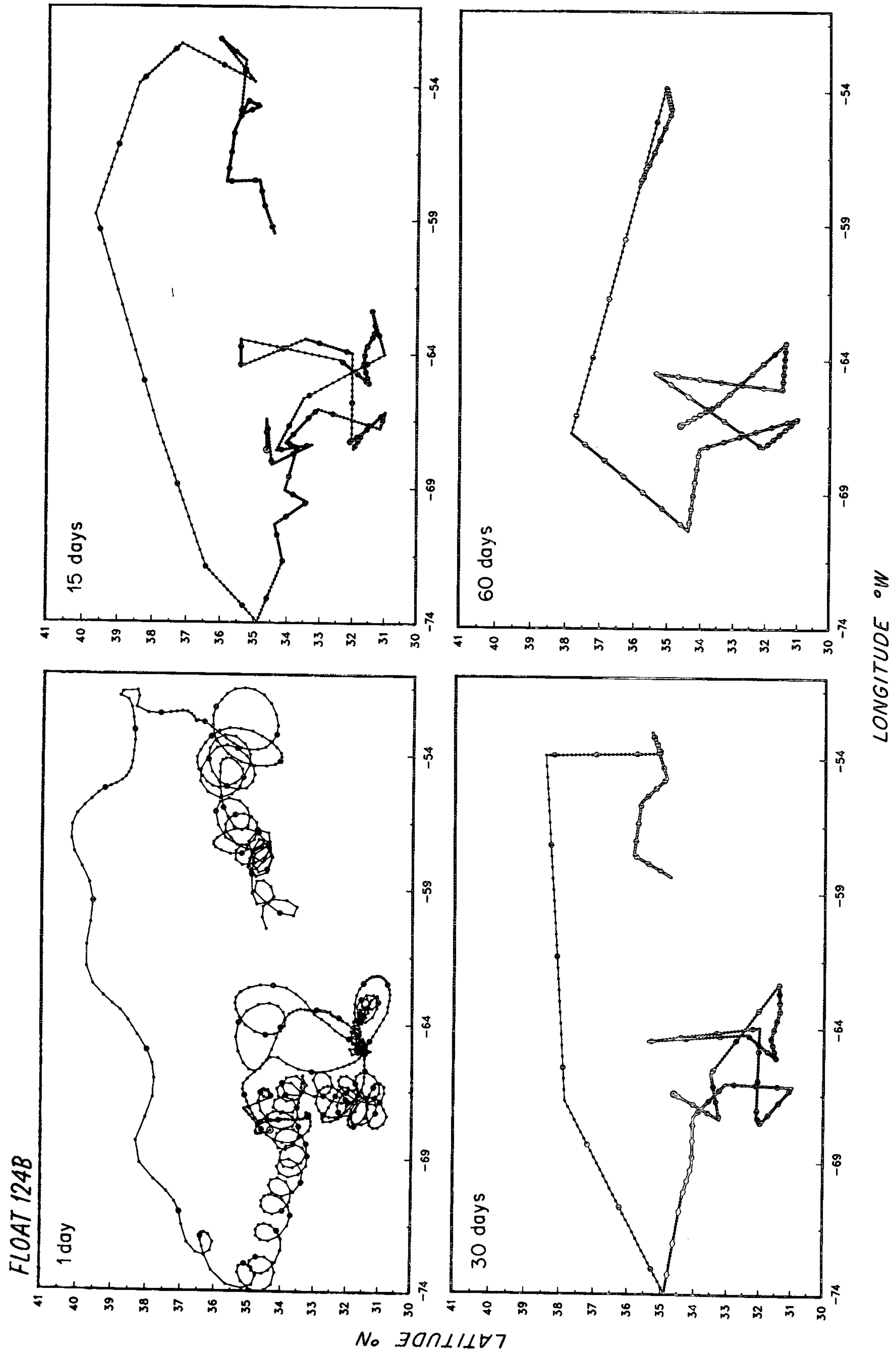

FIG. 2. Trajectory of float 124B that drifted from June 1983 to August 1985, a total of 815 days in the vicinity of the Gulf Stream. Small dots along the trajectories are spaced at 1-day intervals, large dots at 10 days. The original trajectory was subsampled at time intervals labeled in the upper left of each panel.

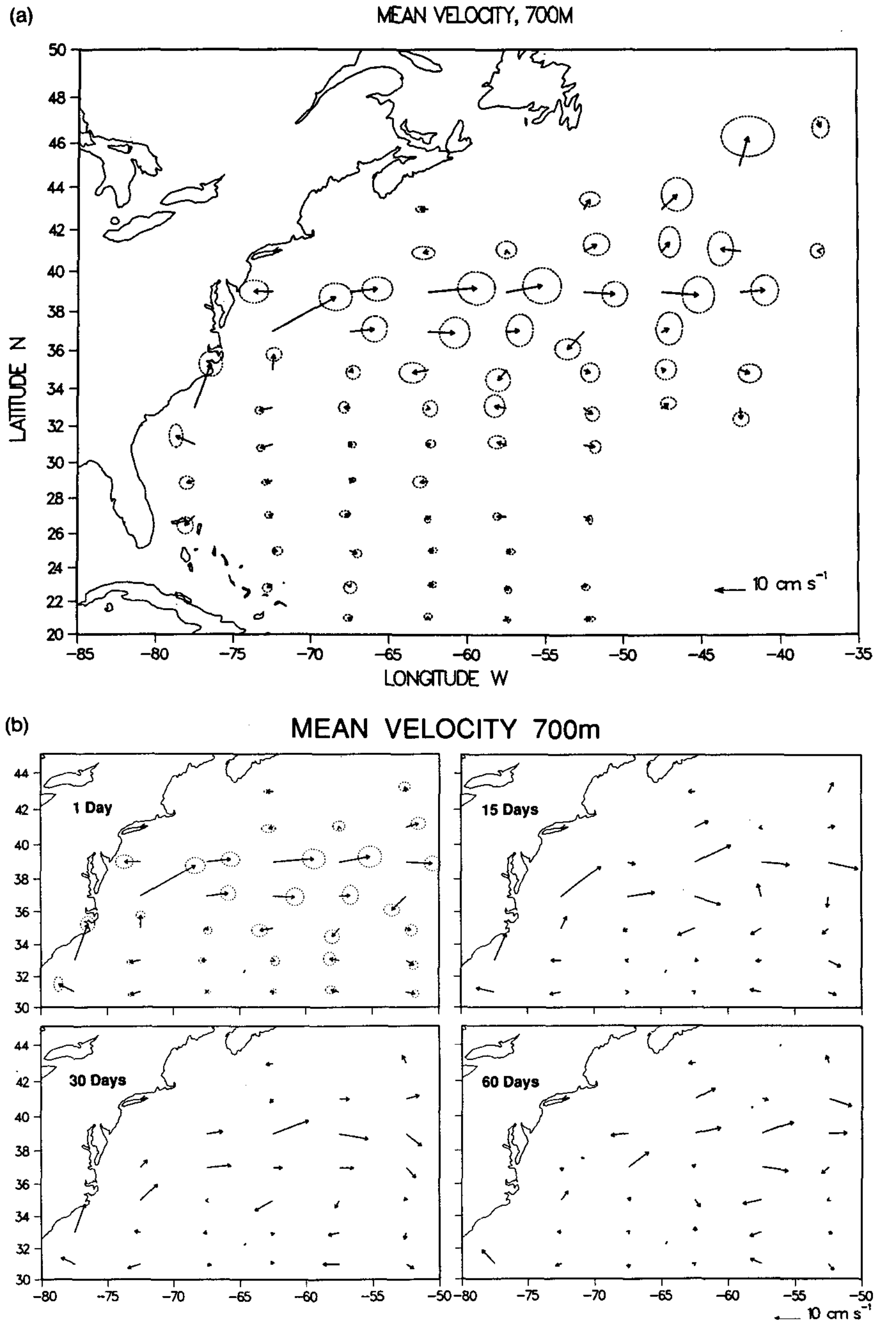

FIG. 3. (a) Mean velocity vectors from data grouped into 2° × 5° boxes. Dashed ellipses show the estimated standard error of each vector. (b) Mean velocity vectors from original and subsampled data in the region 30°–45°N, 50°–80°W. Labels refer to subsampling time intervals.

helpful in addressing some of the deficiencies of real observations.

Mean velocity and EKE distributions were also calculated assuming that the mean velocity between subsampled points was centered geographically midway between them. When these velocity values were grouped into boxes, the resultant mean velocity and EKE fields were noisier and less well defined than in the first technique, especially in the 30- and 60-day subsampled data, and these results are not shown here.

3. Results and discussion

a. *Example of subsampling*

An example of the effect of subsampling a trajectory is shown for float 124B, which had a long (815-day) and interesting trajectory (Fig. 2). This float first looped for 560 days in several different eddies in the Sargasso Sea. Then, it entered the Gulf Stream and for 50 days drifted eastward a distance of 2000 km. Finally, it reentered the Sargasso and for 200 days looped and drifted westward. Subsampling resulted in much lower velocity in the vicinity of eddies, which are no longer resolved. Meanders in the Gulf Stream are also attenuated, but the mean large-scale character is not badly represented by the 15-day sampling, or even the 30-day sampling. With the 60-day sampling, the Gulf Stream is barely recognizable; the float's western extension between 70° and 74°W was cut off, as was the northern excursion near 40°N, 57°W. The longer subsample intervals merge pieces of the Gulf Stream and Sargasso trajectories, blurring the boundary between the two regions and their characteristic velocities.

b. Velocity

Maps of mean velocity in 2° × 5° boxes give a broad view of the general circulation in the Gulf Stream region (Fig. 3a). The swift Gulf Stream arcs out from Cape Hatteras to the Grand Banks, where it splits into a northeastward branch extending into the Newfoundland Basin and an eastward branch between 38° and 40°N (see also Owens 1991). South of 36°N, velocity vectors seem more random and are about the same size as the standard error, which is large due to energetic eddies. Several vectors suggest westward counterflow on both sides of the Gulf Stream (see Richardson 1985), and eastward flow is apparent between 22° and 25°N (see Riser and Rossby 1983; and Owens et al. 1988).

Subsampling changes the magnitude and geographical distribution of velocity values, which changes the calculated mean values in the boxes. Because the eddies cause large errors in the mean velocity, the effect of subsampling is complex (Fig. 3b). A meridional profile of eastward velocity through the Gulf Stream (Fig. 4) shows the current features in better detail: peak mean velocity in the Gulf Stream is 15.2 cm s^{-1} centered near 38°N, width is 5° in latitude from 35° to 40°N, and counterflow is a few centimeters per second.

The 15-day sampling gives a very similar picture of velocity to the 1-day results; the only differences are in minor details. With 30-day sampling, the Gulf Stream is noticeably slower and wider. Peak velocity is reduced to 10.6 cm s^{-1}, and the width is increased to 6° of latitude at the expense of the northern counterflow (Fig. 4). With 60-day sampling, the Gulf Stream is even slower (8.8 cm s^{-1}) and wider (7° in latitude), and the counterflow previously centered near 34°N has virtually disappeared.

In summary, subsampling smoothed out the velocity profile, blurring the Gulf Stream and flanking countercurrents. The 15-day sampling had a minor effect, the 30-day sampling caused noticeable smoothing of velocity, and the 60-day sampling strongly smoothed velocity, totally obscuring the southern flanking countercurrent. In all cases, the eastward flow near 24°N was retained, although details varied.

c. Eddy kinetic energy

A lozenge-shaped maximum in EKE > 500 cm^2 s^{-2} lies along the Gulf Stream between 55°–72°W and 36°–40°W. This area has a peak of 710 cm^2 s^{-2} cen-

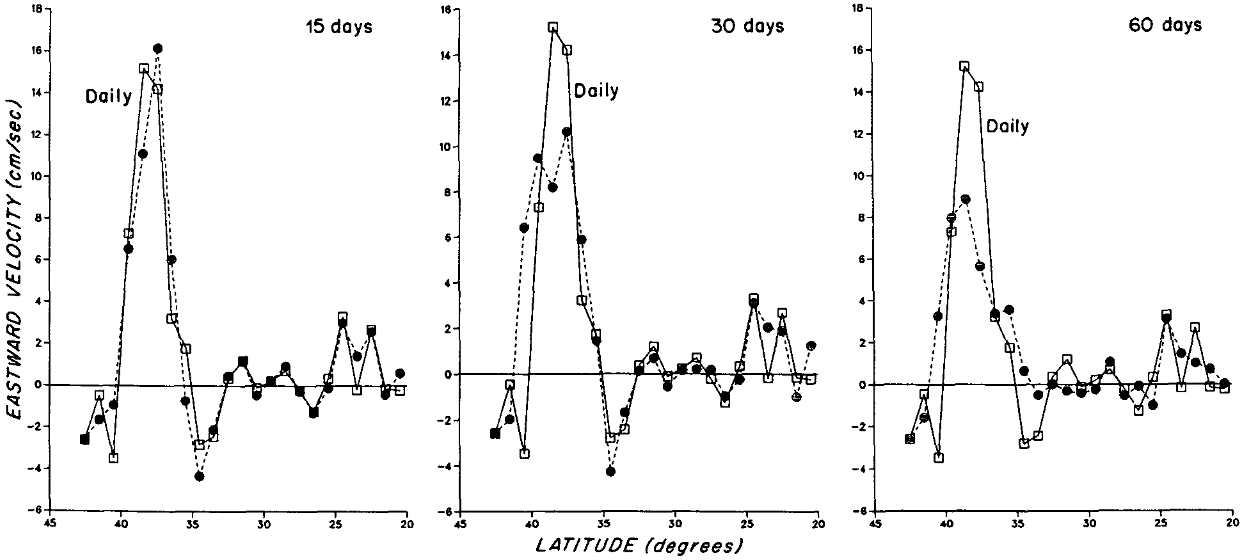

FIG. 4. Mean eastward velocity as a function of latitude across the Gulf Stream near 65°W. Values were calculated by grouping velocity observations into 1° latitude × 10° longitude boxes between 60° and 70°W. The solid line indicates values calculated using daily velocities.

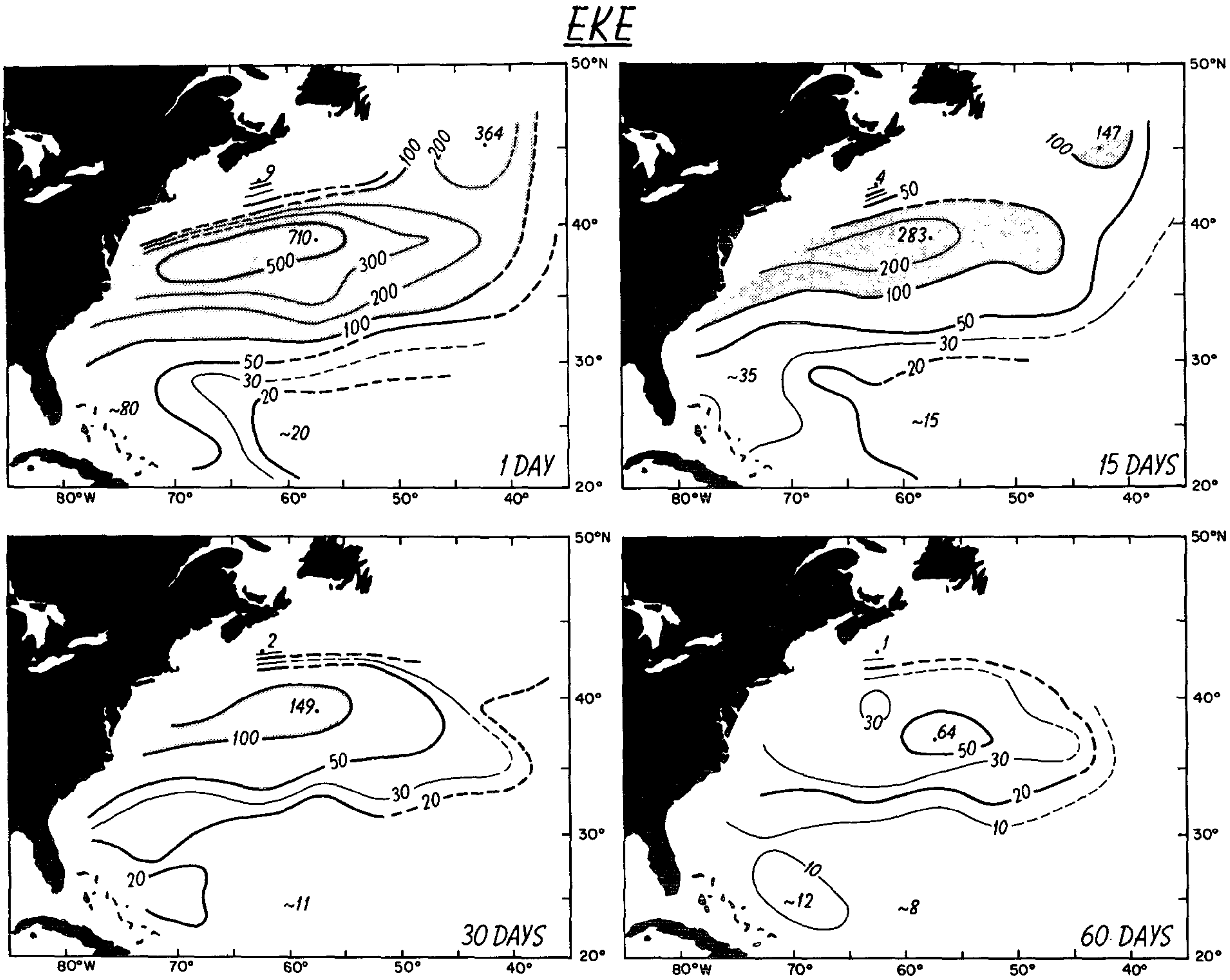

FIG. 5a. Contoured map of EKE (cm^2 s^{-2}) from the 2° × 5° boxes. Dashed contours indicate gaps in the 2 × 5 grid.

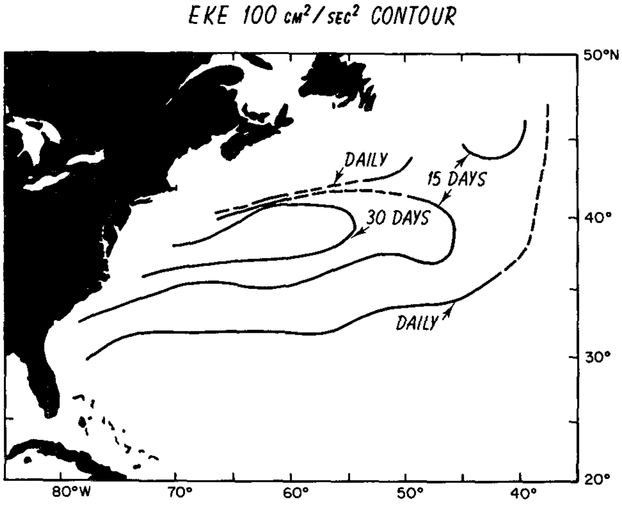

FIG. 5b. Superposition of 100 cm^2 s^{-2} EKE contours.

tered at 39°N, 57.5°W (Fig. 5a). A secondary high of 364 cm^2 s^{-2} occurs in the Newfoundland Basin near 45°N, 42.5°W, and a tongue of values around 80 cm^2 s^{-2} extends southeastward from the Gulf Stream and lies just north of the Bahamas. The EKE decreases rapidly north and south of the Gulf Stream to minima of 20 cm^2 s^{-2} near 25°N, 60°W and of 9 cm^2 s^{-2} at 43°N, 62.5°W.

With 15-day sampling, the general shape of the EKE distribution is similar to the 1-day results, but the amplitude is significantly reduced, especially in the Gulf Stream (Figs. 5 and 6). Peak EKE is diminished from 710 to 283 cm^2 s^{-2}. The least percentage reduction is between 25° and 30°N (Figs. 5 and 6, Table 1). With 30-day sampling, the peak EKE in the Gulf Stream falls to 149 cm^2 s^{-2} and the shape of the contours becomes distorted north of the Bahamas. At 60 days, contours in the vicinity of the Gulf Stream are quite distorted and peak EKE falls to 64 cm^2 s^{-2} and is dis-

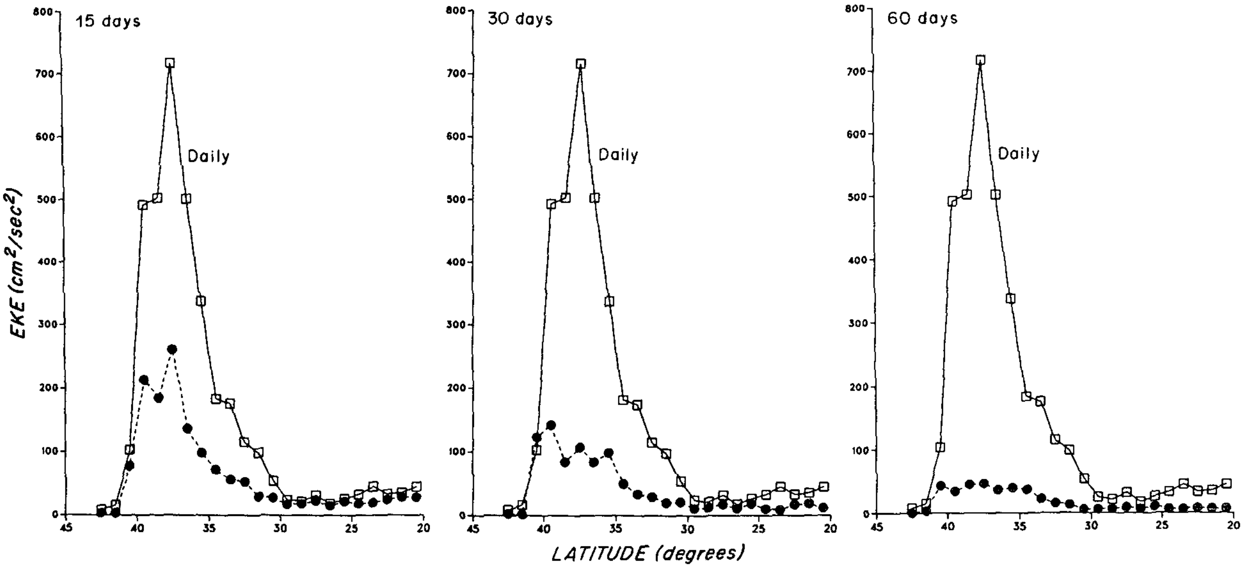

FIG. 6. EKE (cm^2 s^{-2}) as a function of latitude across the Gulf Stream near 65°W.

placed 2° south of its position calculated from 1-day data. The Gulf Stream is reduced to a broad region of relatively constant values around 40 cm^2 s^{-2} between 34° and 41°N, tapering off to values of 10 cm^2 s^{-2} south of 30°N (Fig. 6).

Values of EKE from subsampled data appear to be linearly related to the EKE from the 1-day data, as shown in Fig. 7 and Table 2. This implies that a reasonably correct map of EKE in the vicinity of the Gulf Stream could be obtained from subsampled data if 1) a nearly correct map of the shape of EKE distribution could be obtained from the EKE values, as it can from the 15-day and less so from the 30-day data, and 2) one knows the correct factor relating EKE from subsampled data to that from high temporal resolution data (such as 1 day). The correct factor could be obtained from a few high-resolution float trajectories or current-meter velocity series.

The intercepts of the lines fitted through the data in Fig. 7 lie near 7 cm^2 s^{-2}, suggesting that the lower values of EKE are reduced by a smaller factor than the higher ones (Table 2). A plot of the percentage of original EKE obtained from subsampled data versus sampling interval (Fig. 8) shows that a 10-day sampling interval reduces EKE around 50% and a 52-day interval reduces EKE by 90% in the vicinity of the Gulf Stream.

d. Spectra

Details of the reduction of EKE by subsampling are shown by spectra of float 124B (Fig. 9). The largest peak in 1-day sampling is centered at a relatively high frequency near a period of 12 days due to the loops south of the Gulf Stream and the meanders within it. A second peak centered near 120 days appears to be due to the longer period advection of the eddies and the advection of the float into and out of the Gulf Stream and eddies. As the subsampling interval is increased from 1 day toward 60 days, first the high-frequency peak is eliminated at 15 days, and then the lower-frequency peak is reduced on its high-frequency flank, leaving a peak centered near a period of 240 days for a sampling period of 60 days. South of 30°N in the Sargasso (and not too close to the western

TABLE 1. Reduction of EKE (cm^2 s^{-2}) due to subsampling.

	Sampling interval			
Region	1 day	15 days	30 days	60 days
Gulf Stream	710	283	149	64
North of Bahamas	80	35	20	12
Sargasso Sea	20	15	11	8
Slope water	9	4	2	1

TABLE 2. Relationship between EKE from original and subsampled data along 65°W (see Fig. 7). Slope and intercept are of the least-squares best-fit straight line through the data obtained from 1° latitude × 10° longitude boxes along 60°–70°W.

Sample interval	Mean EKE (cm^2 s^{-2})	Intercept (cm^2 s^{-2})	Slope
1 day	157	0	1.00
15 days	62	7	0.35
30 days	41	8	0.21
60 days	18	6	0.08

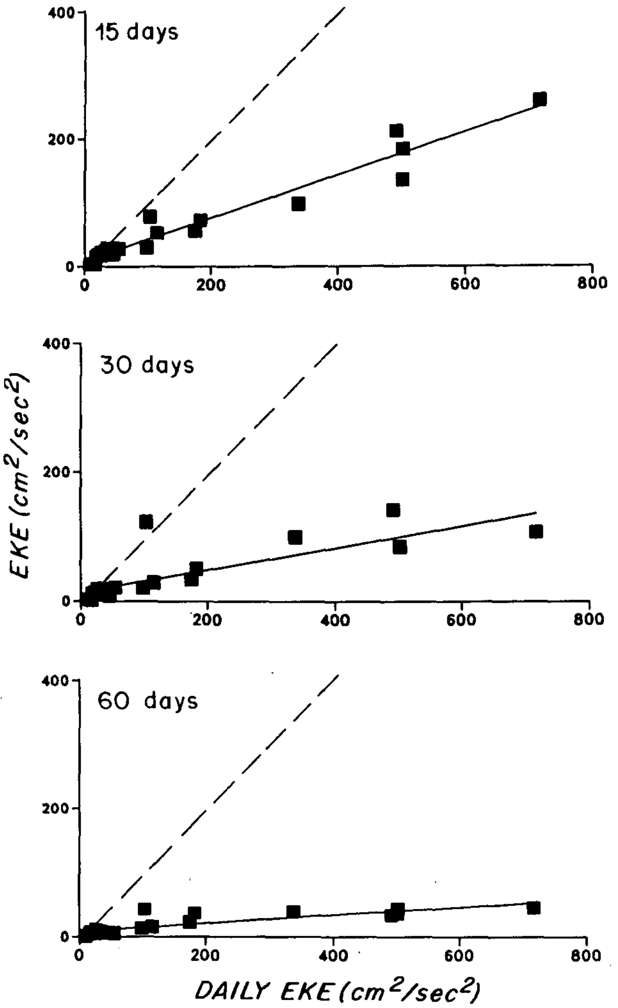

FIG. 7. Scatterplots of EKE calculated from subsampled trajectories plotted against values from original trajectories using 1° × 10° values between 60°–70°W and 20°–43°N. Dashed line is a 1:1 slope. Lines are least-squares best fits to the data (see Table 2).

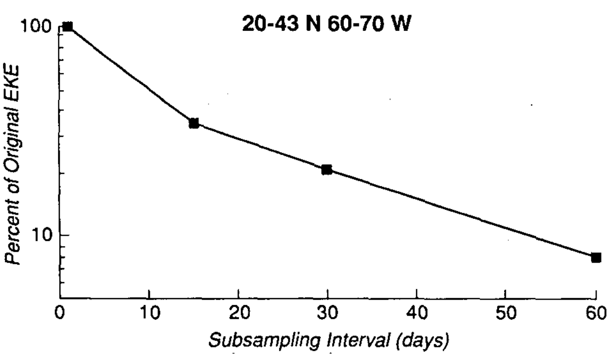

FIG. 8. Percent of original EKE from subsampled data plotted against sampling interval obtained from lines fitted to the data in Fig. 7 and Table 2.

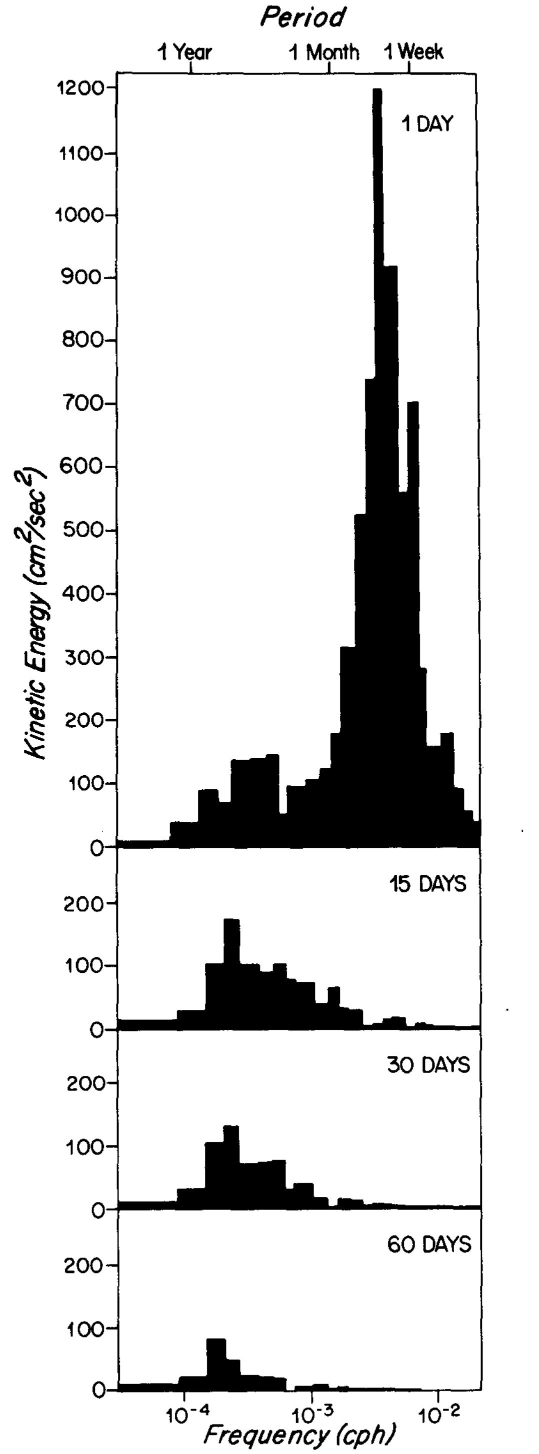

FIG. 9. Energy preserving Lagrangian spectra calculated from float 124B (Fig. 2) using 1-, 15-, 30-, and 60-day subsampled data. Estimates of energy at frequencies higher than the Nyquist frequency ($1/2\Delta T$ where ΔT is the subsampling interval) are meaningless and appear to be due to the way the data were interpolated between subsampled points.

boundary), trajectories have longer time scales of motion, and they are less affected by 15–60-day sampling intervals than trajectories nearer the Gulf Stream or in the Newfoundland Basin. If the Lagrangian spectrum for a region were known, then one could calculate the reduction of energy due to subsampling. The reduction then could be used to obtain nearly correct EKE levels from subsampled data.

4. Summary

These results show that a sampling interval of 15 days reproduces the mean velocity field of the Gulf Stream, including its flanking countercurrents, quite well. At a sampling interval of 30 days, the amplitude and width of the Gulf Stream begin to be noticeably distorted from the 1-day case. At 60 days, the amplitude and width of the Gulf Stream are highly modified, and the southern flanking countercurrent is totally obscured. Subsampling at 15 and 30 days reduces the EKE of the Gulf Stream and the region between 30° and 35°N, which is populated by numerous eddies, by a large amount—80% for 30 days. However, the geographical pattern of EKE is well determined (less so for 30 days). If the real EKE level or Lagrangian energy spectrum were measured at a few points, then the nearly correct EKE distributions could be reasonably well recovered from the subsampled data. This is because the EKE values from original and subsampled EKE data are approximately linearly related for the Gulf Stream region. At 60 days, the geographical distribution of EKE becomes highly distorted. In the Sargasso Sea between 20° and 30°N, where the dominant fluctuations have a longer time scale, mean velocity and EKE are less modified by subsampling than in the Gulf Stream region.

Consideration of the pop-up interval, as determined by the subsampling experiment, suggests the following: shorter subsurface drifts will resolve higher-frequency motion and smaller horizontal scales, but shorter records will be obtained (given a fixed number of cycles). For longer subsurface drifts, longer records will be obtained, but small-scale features, such as the amplitude and width of the Gulf Stream and its countercurrents, will become obscured. This argues for shorter drifts of approximately 15–30 days in the vicinity of the narrow, swift currents like the Gulf Stream and for longer drifts of approximately 60 days in midocean regions, where time and space scales are longer and the mean velocity slower.

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