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Gulf Stream Path Analysis Near the New England Seamounts

WILLIAM J. TEAGUE AND ZACHARIAH R. HALLOCK

Naval Ocean Research and Development Activity, Stennis Space Center, Mississippi

As part of the Naval Ocean Research and Development Activity's Regional Energetics Experiment, 12 inverted echo sounders (IESs) were deployed from June 1985 to July 1986 in two arrays across the historical mean path of the Gulf Stream near 67°W and 58°W, slightly upstream and downstream of the New England Seamount chain. Gulf Stream positions and directions were computed at half-day intervals for adjacent IES pairs. Levels of variability at the two array locations were similar, but the characteristics of the meanders, in terms of propagation and current direction, were quite different. Evidence was found for a quasi-stationary meander near 58°W. Features deduced from IES measurements are compared with concurrent infrared, air-dropped expendable bathythermograph, and Geosat altimetry observations.

1. INTRODUCTION

The ability to monitor and describe fluctuations in the Gulf Stream and associated rings and eddies is essential for understanding the evolution of such features. Over the past decade, there has been a considerable effort to study the time dependent motion of the Gulf Stream [*Brooks and Bane*, 1983; *Halliwell and Mooers*, 1983, *Johns and Watts*, 1985, 1986; *Watts and Johns*, 1982]. Observations have shown that the Gulf Stream is dominated by change with a broad spectrum of temporal and spatial scales.

Gulf Stream variability is primarily the result of the lateral meandering of the current, while the instantaneous, cross-stream profile is remarkably constant [*Halkin and Rossby*, 1985]. As a result, long-term average cross-stream profiles [e.g., *Richardson*, 1985] are much broader than the instantaneous Gulf Stream and are never realized at any single time. Gulf Stream meanders east of 67°W are typically 100–200 km in amplitude [*Hansen*, 1970], and their characteristics change east of the New England Seamount Chain (NESC) [*Fuglister*, 1963; *Cornillon*, 1986; *Richardson*, 1983], but there is some controversy as to the nature of this change.

Detailed, Eulerian descriptions of Gulf Stream fluctuations west of about 67°W, involving the use of inverted echo sounder (IES) arrays, have shown propagating meanders with wavelengths of several hundred kilometers and amplitudes of 10–30 km. East of Cape Hatteras these meanders grow, in an apparent spatial instability [*Watts and Johns*, 1982; *Tracey and Watts*, 1986]. East of the NESC, such descriptions are less complete, being limited primarily to subsurface current meter observations [e.g., *Hendry*, 1982]. Furthermore, satellite infrared imagery tends to be less reliable in this region owing to frequent cloud contamination.

In this paper we present a description of the Gulf Stream, at two locations upstream and downstream of the NESC, based on 13 months of IES observations. The salient result is that although the levels of variability in the two locations are similar, the characteristics of the meanders, in terms of propagation and current direction, are quite different. Results are compared with concurrent infrared (IR), air-dropped expendable bathythermograph (AXBT) and Geosat altimetry observations; generally good agreement is found.

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2. BACKGROUND

As the Gulf Stream emerges from the Straits of Florida it is bounded to the west by the continental margin and flows northward in depths of 500 to 800 m. Downstream of Cape Hatteras the stream no longer follows the shelf break but continues eastward at depths greater than 4000 m. In this region it is bounded by slope water. Maximum latitude is reached between 55° and 60°W; from there the Gulf Stream flows southeastward along the western side of the Newfoundland Ridge which extends southeastward from the Grand Banks [*Richardson*, 1981]. The path of the Gulf Stream is characterized by meanders, appearing as lateral shifts of the baroclinic structure. Downstream of Cape Hatteras the meander envelope is 200–300 km [*Watts and Johns*, 1982] and is dominated by long-wavelength (200–400 km), large-amplitude meanders with propagation speeds that range from several kilometers per day to 40 km per day [*Hansen*, 1970, *Robinson et al.*, 1974]. *Halliwell and Mooers* [1979], using weekly satellite infrared images to study the Gulf Stream surface temperature front between 74°W and 65°W, found that the wave number spectrum is broadly peaked near wavelengths of 320 km, with which they associated periods of 50 days and speeds of 6–7 km d^{-1}. Some meanders south of Nova Scotia were found to be quasi-stationary in the early shipboard surveys [*Fuglister and Worthington*, 1951; *Fuglister*, 1963].

The Gulf Stream crosses the NESC, which extends southeastward from the continental shelf off Georges Bank near 40°N, 67°W to the Sohm Abyssal Plain near 34°N, 56°W. The seamounts occupy a significant portion of the deep water region, rising 2 to 3 km above the seafloor, where they influence the deep flow of the Gulf Stream. Evidence from drifting buoys suggests that the influence of the NESC extends to the sea surface, where it can generate intense mesoscale eddies or cause a deflection of the stream [*Richardson*, 1981]. Data from these buoys show an abrupt increase in meander amplitude near the New England Seamounts, in agreement with *Fuglister* [1963]. However, *Hansen* [1970] observed that the envelope of Gulf Stream northern edges increased almost linearly from 75°W to 55°W, not abruptly at the New England Seamounts. *Cornillon*

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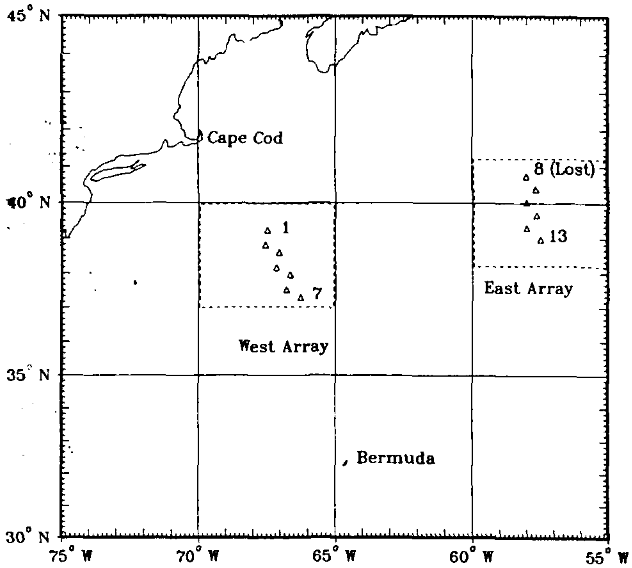

Fig. 1. IES locations.

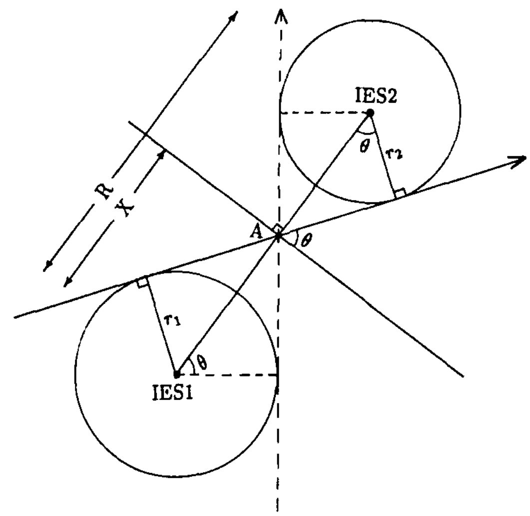

Fig. 3. The crossing location, point A, and crossing angle θ for the Gulf Stream path between a pair of IES sites are determined by the distance R separating the sites, the distance x from the IES site to the crossing location, and the distance r from the IES site to the Gulf Stream center. Two paths and four directions are possible.

[1986], in an analysis of Gulf Stream northwall positions by satellite IR imagery, supports the hypothesis of "increased meandering" across the NESC but maintains that the envelope of overall variability remains constant in the region. This result is also consistent with *Auer*'s [1987] analysis of 5 years of IR data. With a two-layer, primitive equation, eddy-resolving model, *Thompson and Schmitz* [1989] show that bottom topography such as the NESC profoundly influences the characteristics of the Gulf Stream. The implication of these results is that meanders with wavelengths up to several hundred kilometers increase in amplitude and/or become more convoluted (less sinusoidal) going eastward across the NESC, but there are longer-wavelength fluctuations, particularly to the west of the NESC, which contribute to the overall variance envelope of northwall positions.

3. Data

A major component of the field activities for the NW Atlantic Regional Energetics Experiment (REX) [*Mitchell et al.*, 1987] is focused on collecting and analyzing data from two arrays of bottom-moored IESs with pressure gauges deployed in the Gulf Stream region, near 58°W and 67°W, slightly up (west) and downstream (east) of the NESC in water depths ranging from 3400 m to 5000 m (Figure 1). Other major components of the REX include the analysis of sea surface topography data provided by the U.S. Navy Geosat, regional AXBT surveys, and numerical modeling studies. The IES arrays were positioned across the historical mean path of the Gulf Stream and were in place from June 1985 to July 1986. The IES sites were staggered to better recover current direction. Twelve of thirteen instruments were recovered (the instrument not recovered was located, but would not release its anchor).

Pressure, temperature, ambient noise, and a burst of 24 round-trip, acoustic travel times to the surface were sampled

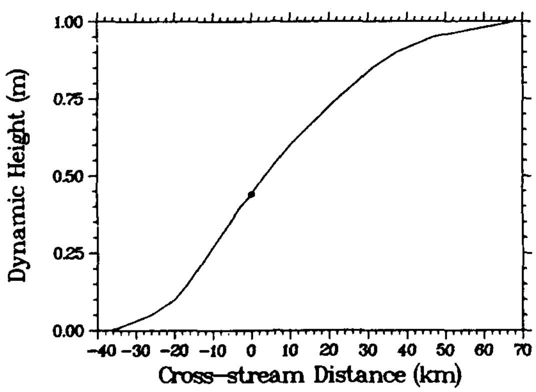

Fig. 2. Cross-stream profile of dynamic height obtained from a Gulf Stream model described by *Kao* [1980]. Cross-stream distance is 0 at a dynamic height of 0.44 m.

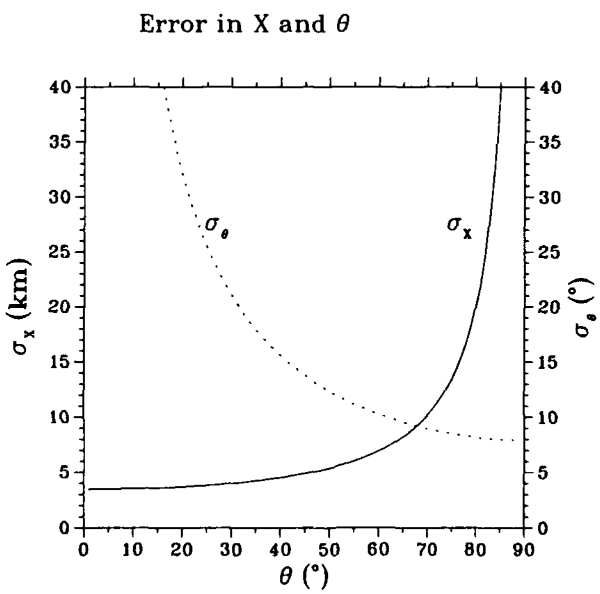

Fig. 4. Error in x (σ_x) and error in θ (σ_θ) are related to θ. For the error analysis we assume the error in CSP slope is ±0.2 dyn cm km^{-1} and that the error in IES dynamic height is ±7 dyn cm.

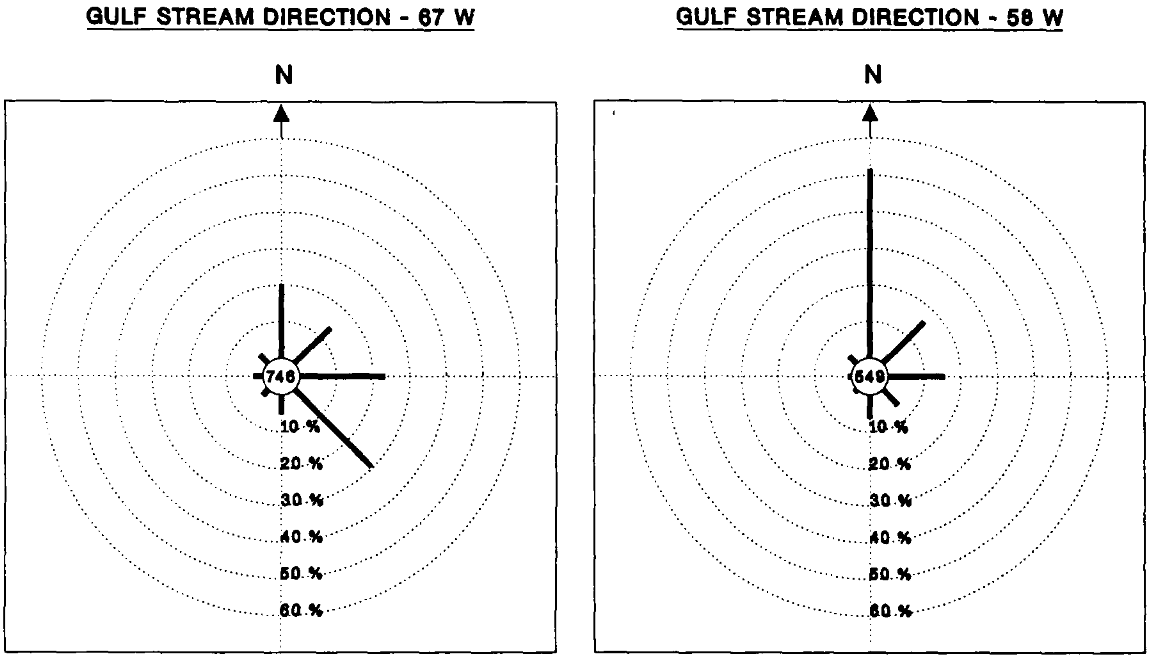

Fig. 5. Gulf Stream direction (*a*) for 746 half-day realizations at the western site and (*b*) for 549 half-day realizations at the eastern site.

hourly. Single travel times were computed from three consecutive bursts (72 realizations) using the mode of the Rayleigh distribution [*Watts and Rossby*, 1977]. This 3-hour running average reduced much of the noise in the data that resulted from a travel time detector problem due to an abnormally high number of late or missed echoes. In regions such as the Gulf Stream the dominant signal in records of travel time is baroclinic mesoscale variability resulting from meandering of the Gulf Stream and the passage of rings and eddies; minimums in travel times correspond to the Sargasso side of the Gulf Stream, while maximums correspond to the slope side. Tidal frequency fluctuations are also evident with amplitudes of about 10% of that of the mesoscale features. For Gulf Stream tracking purposes, the data were low-pass filtered at 40 hours and subsampled at half-day intervals.

4. METHOD

Watts and Rossby [1977] showed the relation of dynamic height to IES-measured travel time. This relation is linear, to a good approximation, and can be expressed as

$$D = B(\tau - \bar{\tau}) + C \qquad (1)$$

where τ is travel time and $\bar{\tau}$ is the time average of τ. For the REX area, $B = -3.13 \pm 0.07$ dyn cm ms^{-1} [*Hallock*, 1987]. C is unknown without additional information but can be estimated from the IES records as follows. We assume that during those periods where τ is at a nearly constant minimum, the IES is on the Sargasso side of the Gulf Stream. Conversely, when τ is at a nearly constant maximum, the

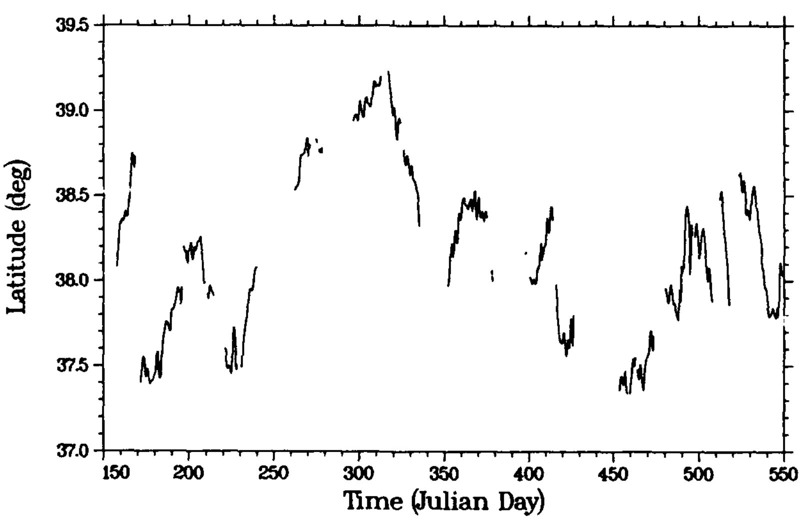

Fig. 6. North wall latitude position for Gulf Stream direction between 30° and 150°. For convenience, Julian day continues to increment past the end of year.

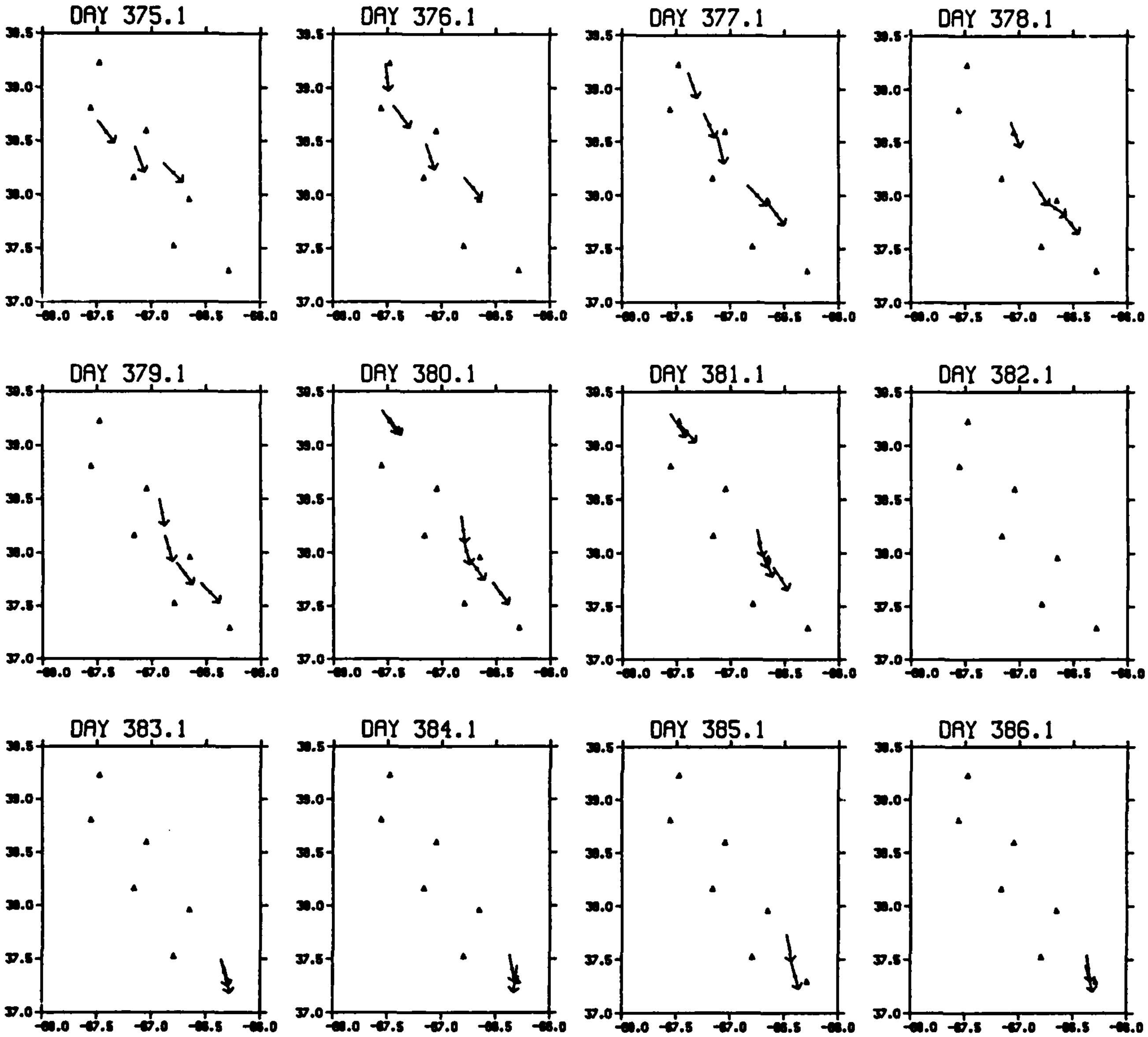

Fig. 7*a*

Fig. 7. Propagation of a meander through the western array: (*a*) southward leg, (*b*) northward leg. Day 375 corresponds to January 10, 1986.

IES is on the slope side. We then arbitrarily set $D = 0$ on the slope side, and C is determined for all records where the slope periods are present in the data. For records (one or two in each array) where both slope and Sargasso periods are evident, the difference of dynamic height across the Stream, $\Delta D = B\Delta\tau$, is derived. ΔD is assigned to the value of D for Sargasso periods in records where slope periods cannot be found, determining C for those cases. With B and C determined for each record, time series of dynamic height relative to the level of the slope side of the Gulf Stream were derived.

We describe the evolution of the Gulf Stream path using a procedure based on that used by *Watts and Johns* [1982]. A constant, cross-stream profile (CSP) of dynamic height is assumed (Figure 2). This profile, obtained from a Gulf Stream model described by *Kao* [1980], was found consistent with Seasat altimetry data and hydrographic observations. The horizontal scale of the profile has been adjusted to be consistent with a set of XBT sections acquired in the REX area, and the vertical scale has been adjusted to ΔD. The "center" of the Gulf Stream is defined to have a dynamic height of 0.44 dyn m relative to the slope level and is about 45 km to the Sargasso side of the northwall defined by the 15°C isotherm at 200-m depth. The center of the Gulf Stream (as defined above) is required to pass between IES sites before a position is calculated.

Using this adjusted CSP, time series of the perpendicular, horizontal distance r to the Gulf Stream center from an IES is calculated from the corresponding dynamic height series. The crossing angle θ of the Gulf Stream path between a pair of IES sites (Figure 3) is found by

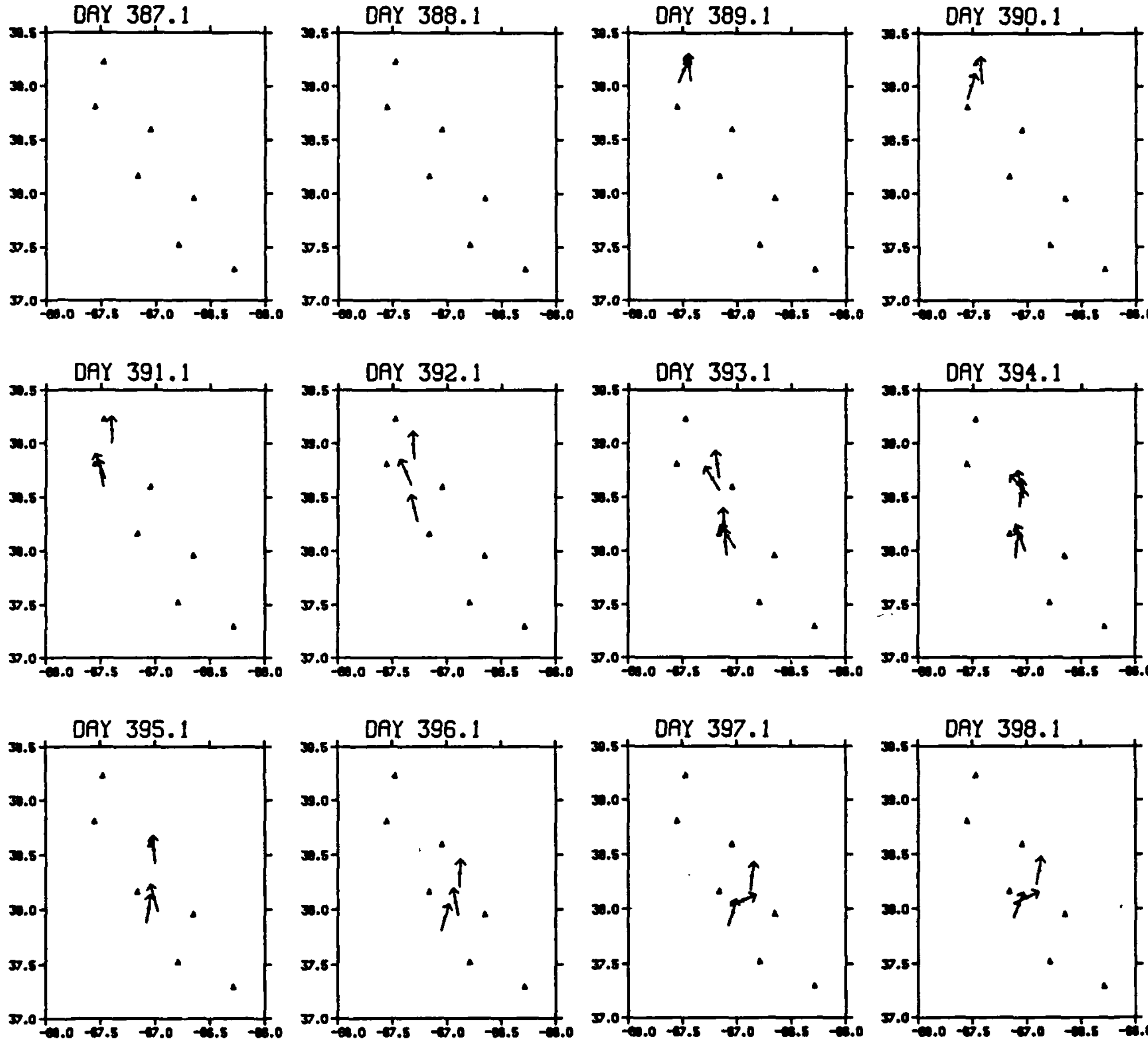

Fig. 7*b*

$$\theta = \cos^{-1}\left(\frac{r_1 + r_2}{R}\right) \tag{2}$$

where R is the distance between the sites. The crossing location between the sites, point A, is defined by its distance, x, from one of the sites along the line connecting the sites.

$$x = \frac{r_1}{\cos\theta} = \frac{Rr_1}{r_1 + r_2} \tag{3}$$

Note that two paths and four directions are possible. Two directions can be automatically discarded by inspecting dynamic height highs and lows. A third direction is manually discarded by inspection of previously accepted flow directions. Once x and θ are found, they are transformed to the geographic coordinates of the entire IES array. Gulf Stream positions and directions were computed at half-day intervals for adjacent IES pairs for both eastern and western arrays. Position and direction were often found for several IES pairs during each time realization.

To minimize the error in the calculated distances, only the nearly linear portion of the CSP is used: IES-derived dynamic heights are restricted to the 0.1 to 0.9 dyn m portion of the profile. A horizontal distance error of about [illegible] km results from an error of 1 dyn cm, essentially the inverse of the slope of the CSP. For a strictly linear, constant CSP, a change in observed slope implies only a change in direction. Hence if our estimates of the CSP slope are in error, the inferred direction will also be in error.

It is useful to estimate the errors induced in θ and x by errors in both the measured dynamic heights as well as the CSP slope. For the error analysis we assume the CSP is linear with slope $m = 1.4 \pm 0.2$ dyn cm km^{-1}. The error in dynamic height, which results primarily from uncertainties in the travel time to dynamic height conversion, is estimated to be about ± 7 dyn cm [*Hallock*, 1987]. With this linear approximation, the distances r_i are just

$$r_i = \left|\frac{D_i'}{m}\right| = \pm\frac{D_i'}{m} \tag{4}$$

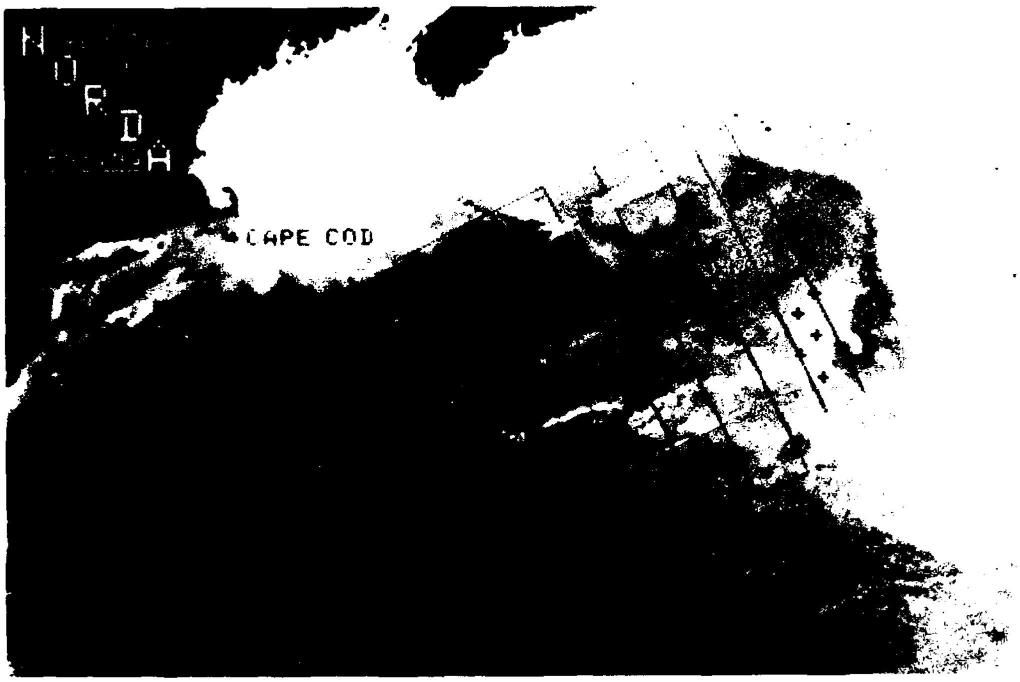

Fig. 8*a*

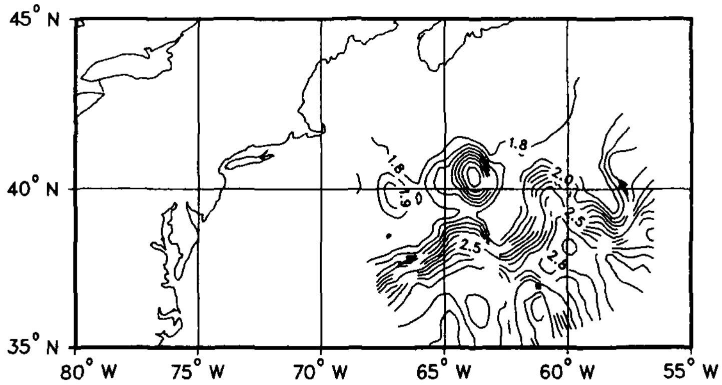

Fig. 8*b*

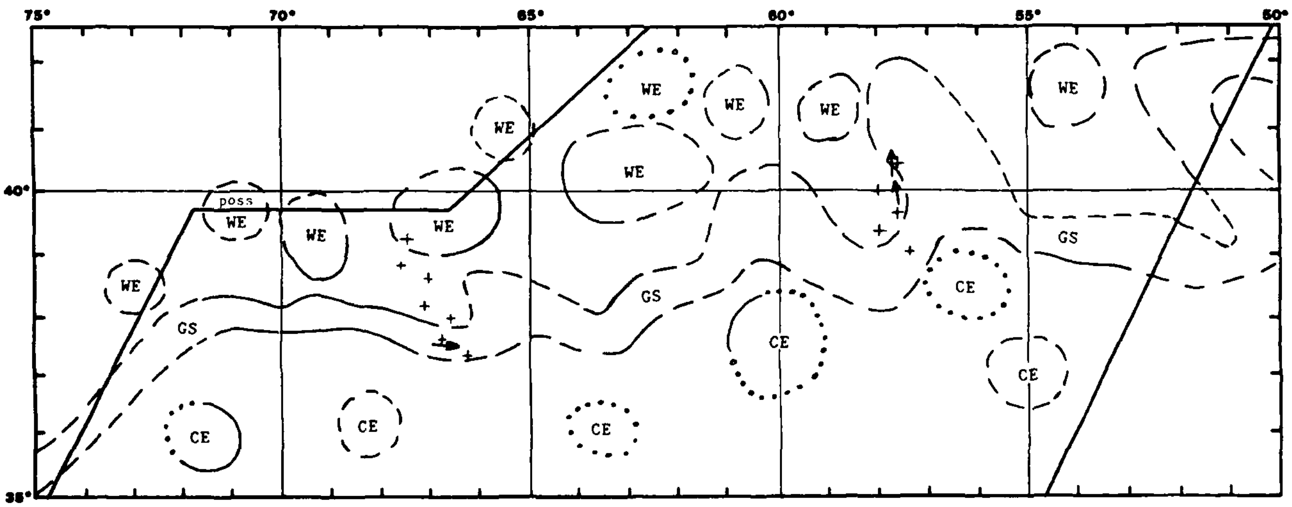

Fig. 8*c*

Fig. 8. (*a*) IR image from August 13, 1985 (pluses, IES locations; solid lines, AXBT track lines for August 13, 15, 17, and 19). (*b*) IES-derived Gulf Stream position and direction superimposed on the dynamic height field (see arrows near 67°W and 58°W). (*c*) IES-derived Gulf Stream position and direction superimposed on August 9 GOAP mesoscale analysis (pluses, IES locations; solid line, altimeter derived; dashed line, IR derived; dotted line, estimated; heavy solid line, GOAP boundary; GS, Gulf Stream; CE, cold eddy; WE, warm eddy).

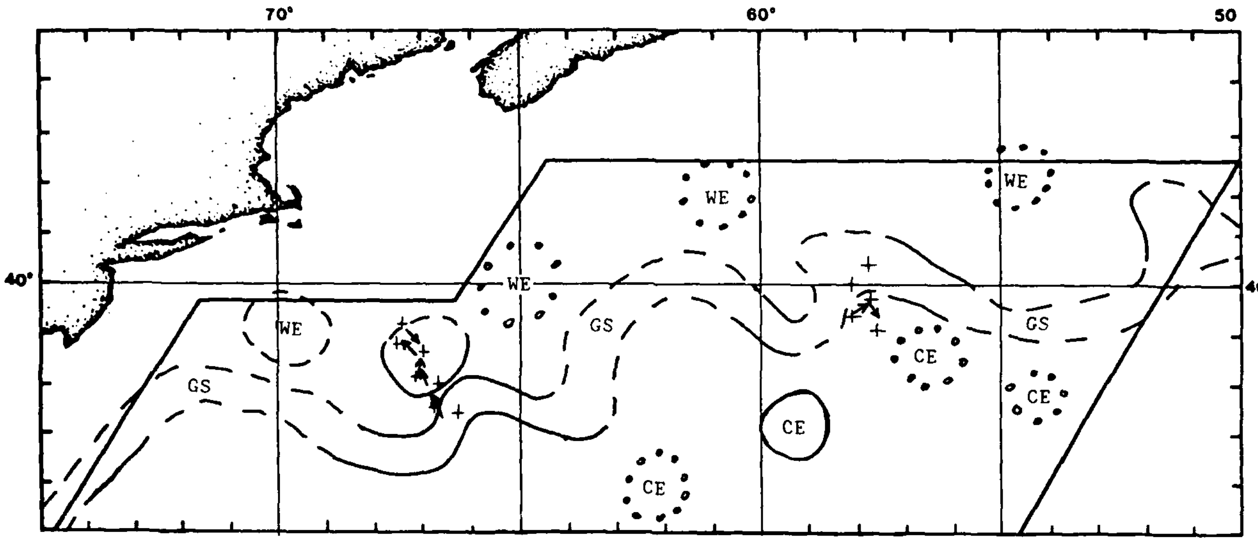

Fig. 9. IES-derived Gulf Stream position and direction superimposed on the October 2 (day 275) GOAP mesoscale analysis.

where $D_i' = D_i - D_0$; and $D_0 = 0.44$ dyn m. The expressions for θ and x become

$$x = \frac{D_1' R}{D_1' - D_2'} \qquad (5)$$

(since we know $D_1' D_2' < 0$) and

$$\cos \theta = \pm \frac{D_1' - D_2'}{mR} \qquad (6)$$

We seek the uncertainties in x, θ in terms of the uncertainties of m and D'. In general, the uncertainty of a function $w(u, v)$ [*Bevington*, 1969] can be expressed in terms of the uncertainties of u, v as follows:

$$\sigma_w^2 \approx \sigma_u^2 \left(\frac{\partial w}{\partial u}\right)^2 + \sigma_v^2 \left(\frac{\partial w}{\partial v}\right)^2 + 2\sigma_{uv}^2 \left(\frac{\partial w}{\partial u}\right)\left(\frac{\partial w}{\partial v}\right) \qquad (7)$$

where σ_w is the uncertainty of w, etc., and σ_{uv} is the covariance of the errors of u and v. For our case we assume the errors are uncorrelated ($\sigma_{mD_1} = \sigma_{mD_2} = \sigma_{D_1D_1} = 0$) and $\sigma_{D_1}^2 = \sigma_{D_2}^2 \equiv \sigma_D^2$. Introducing our expressions for x, θ into (7), with some rearranging we have

$$\sigma_x = \sigma_D \frac{(1 + 2x^2/R^2 - 2x/R)^{1/2}}{m \cos \theta} \qquad (8)$$

$$\sigma_\theta = \frac{(2\sigma_D^2 + R^2 \cos^2 \theta \sigma_m^2)^{1/2}}{mR \sin \theta} \qquad (9)$$

We note that σ_x ranges from $\sigma D(2^{1/2} m \cos \theta)^{-1}$ to $\sigma D(m \cos \theta)^{-1}$ for x ranging from $R/2$ to either 0 or R. These are nearly the same so we use the first case. The dependences of σ_x, σ_θ on θ are plotted in Figure 4. We see that as θ approaches 90°, σ_x becomes unbounded; This is reasonable because the orientation of the inferred flow is along the line between the sites, rendering x meaningless; σ_x is 10% of R (5 km) for $\theta \approx 50°$ and reaches a maximum acceptable value of 50% of R (25 km) for $\theta \approx 84°$. Near $\theta = 0$, σ_θ becomes unbounded; σ_θ becomes equal to θ at about 25°, thus defining a band of uncertainty for directions <25° on either side of $\theta = 0$. For θ near 90°, σ_θ approaches a minimum value and is seen to be independent of σ_m. Hence for a pair of IESs there are flow directions for which either direction or position cannot be well defined. However, because the sites are not positioned along a single line but are arranged in a series of triangles, much of this indeterminacy can be resolved. In cases where at least two determinations can be made for a triangular subarray, at least one of the directions will be associated with large θ and one of the positions with small θ, thus minimizing the error for a combined determination. These considerations were used to edit the final time series of vectors.

5. OBSERVATIONS

A typical half-day sample consists of two or more path realizations. An average position and direction was calculated for each sample. The Gulf Stream is found to sweep throughout the entire north-south range of the IES sites. For the western array (67°W), the mean direction over the recording period is 92°. However, direction of flow ranges from northward to southeastward (Figure 5*a*). Furthermore, while the flow is to the southeast 30% of the time and to the north 20% of the time, flow is to the east only 23% of the time.

Flow is quite different at the eastern array site (58°W). Here direction is primarily northward with a mean direction of 16°. Flow is northward 52% of the time while eastward only 17% of the time (Figure 5*b*). IES-derived paths of the Gulf Stream indicate a quasi-stationary meander with the northern leg typically at 58°W.

Gulf Stream north wall locations were computed for each half-day sample for the western array and lie about 0.4° north of our mid-stream estimate for an eastward flowing stream. North wall positions make sense only for a predominately eastward flow; hence only the positions corresponding to Gulf Stream directions between 30° and 150° are considered (Figure 6). Maximum northward excursion of the stream occurs near Julian day 300. Mean latitude for the Gulf Stream at the western array site is 38.3, near the center of the western array. For the eastern array, a north wall computation was not considered meaningful.

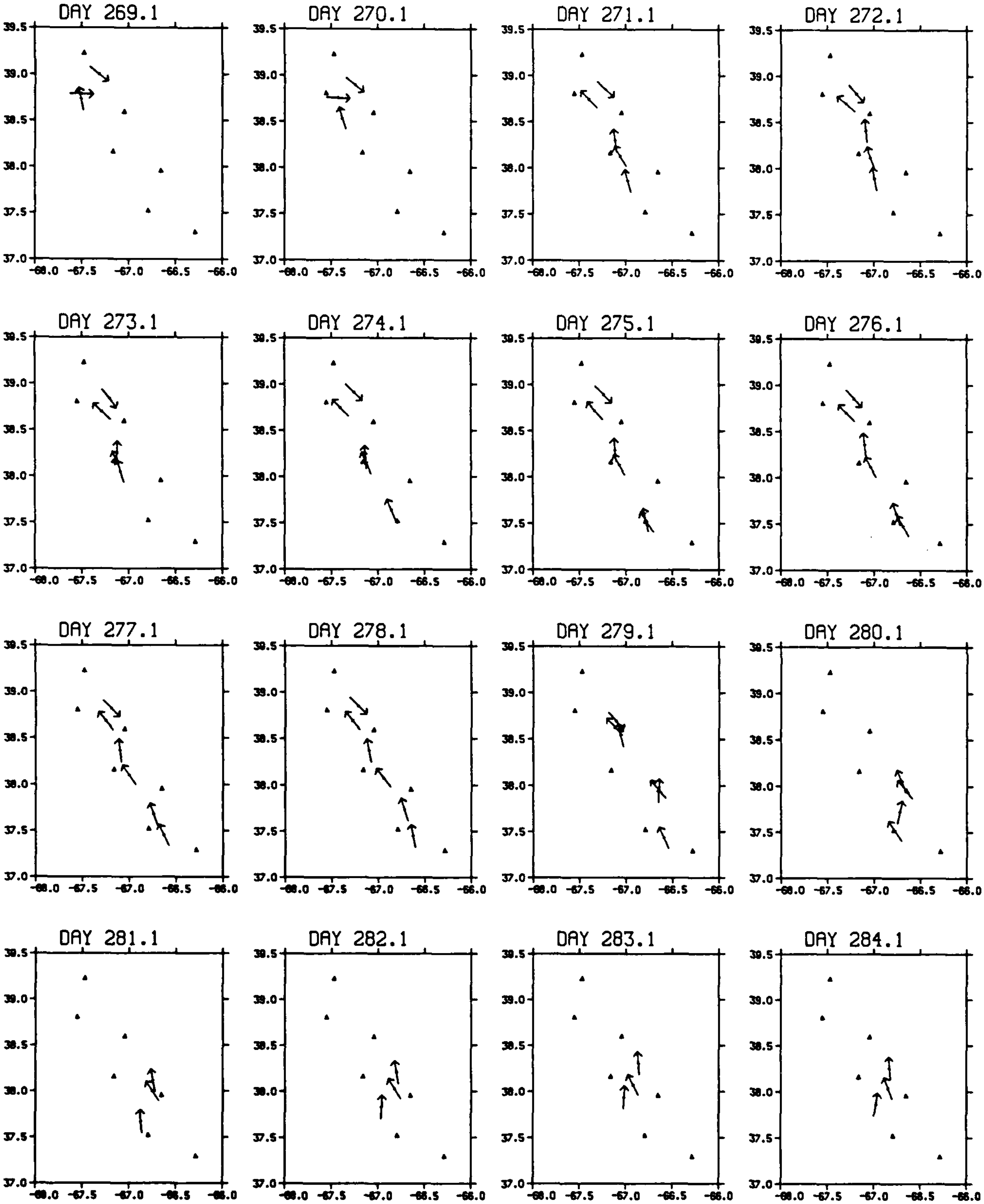

Fig. 10. IES representation of the Gulf Stream path for the western array for days 269 to 284 (September 26 to October 11).

IES sites for both eastern and western arrays were designed to monitor a predominantly eastward flowing Gulf Stream. For the western array, this design worked quite well. The stream passed through this array 95% of the time. The stream passed through the eastern array only 75% of the time. However, this percentage would have been considerably less if the quasi-stationary northward flow were a few tens of kilometers to the east or the west. More east-west

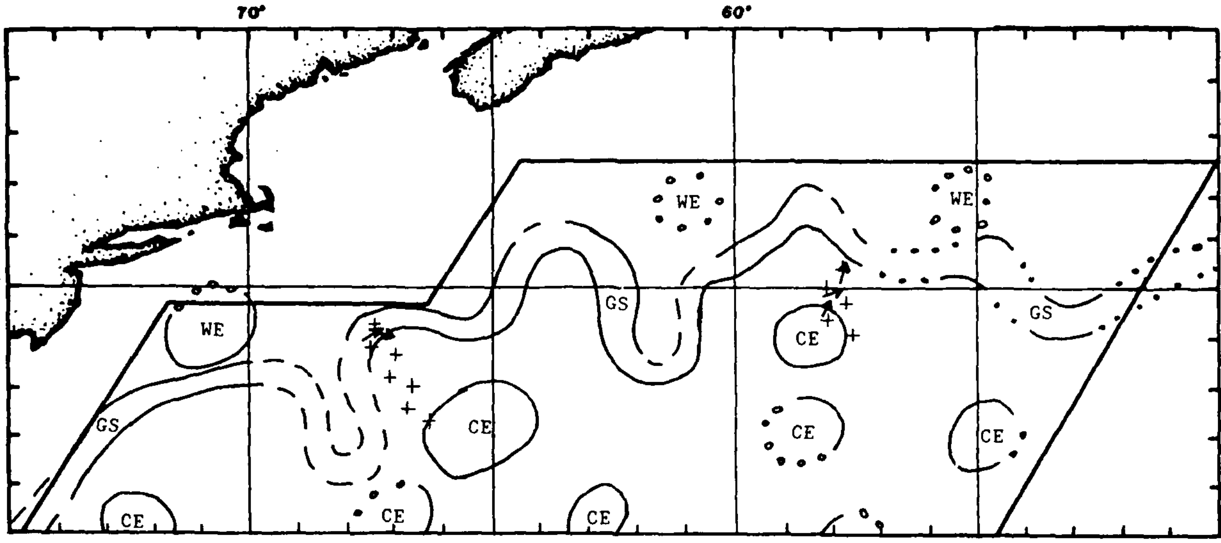

Fig. 11*a*

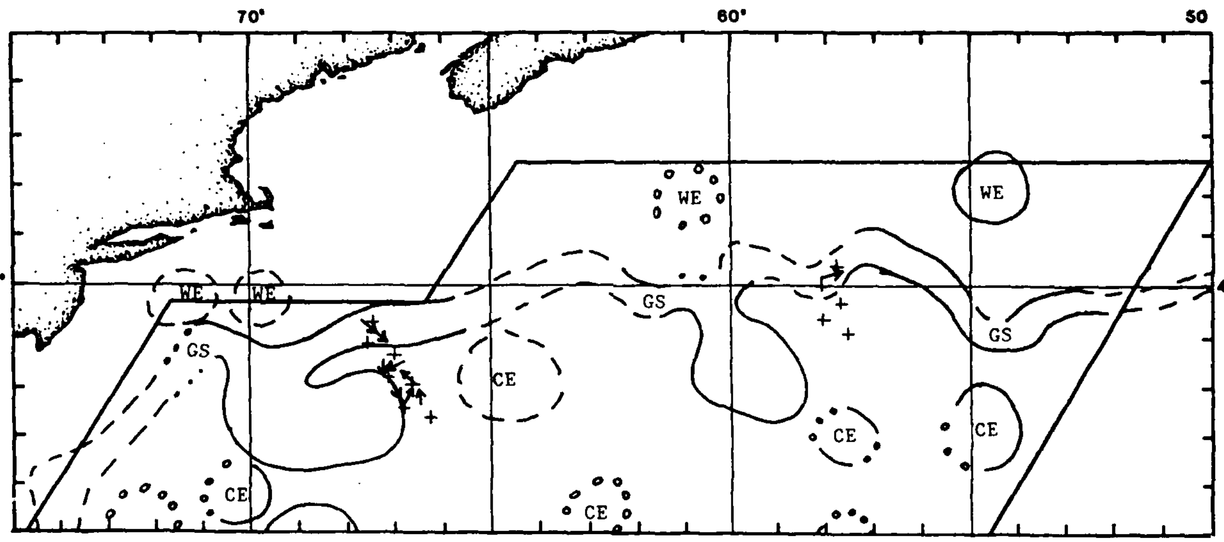

Fig. 11*b*

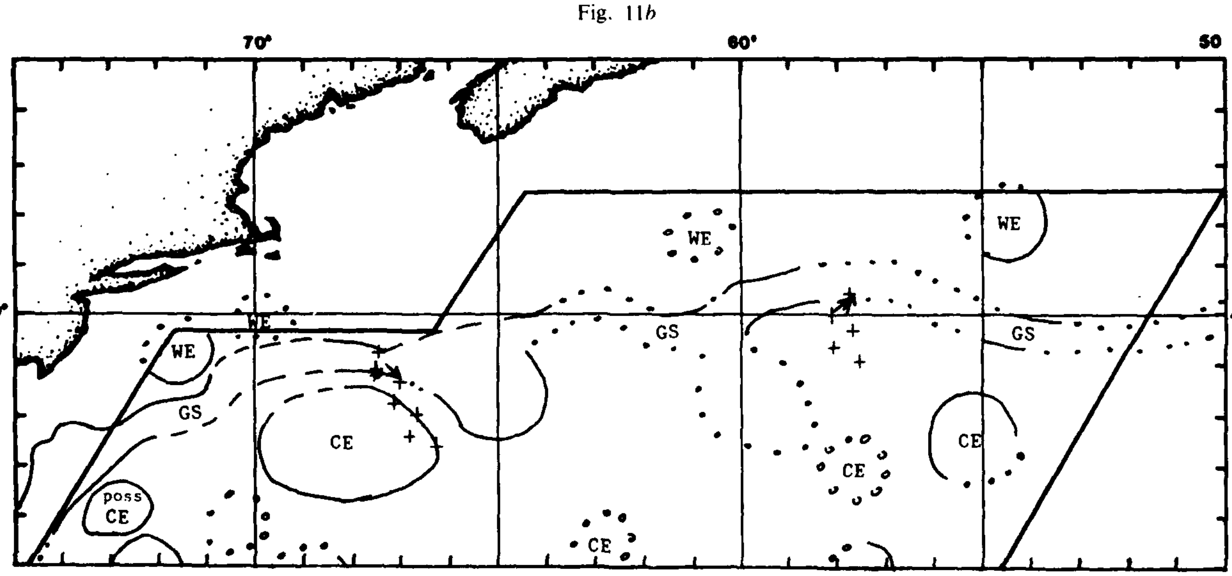

Fig. 11*c*

Fig. 11. IES-derived Gulf Stream position and direction superimposed on GOAP mesoscale analyses for (*a*) November 2 (day 306), (*b*) November 14 (day 318), and (*c*) November 21 (day 325).

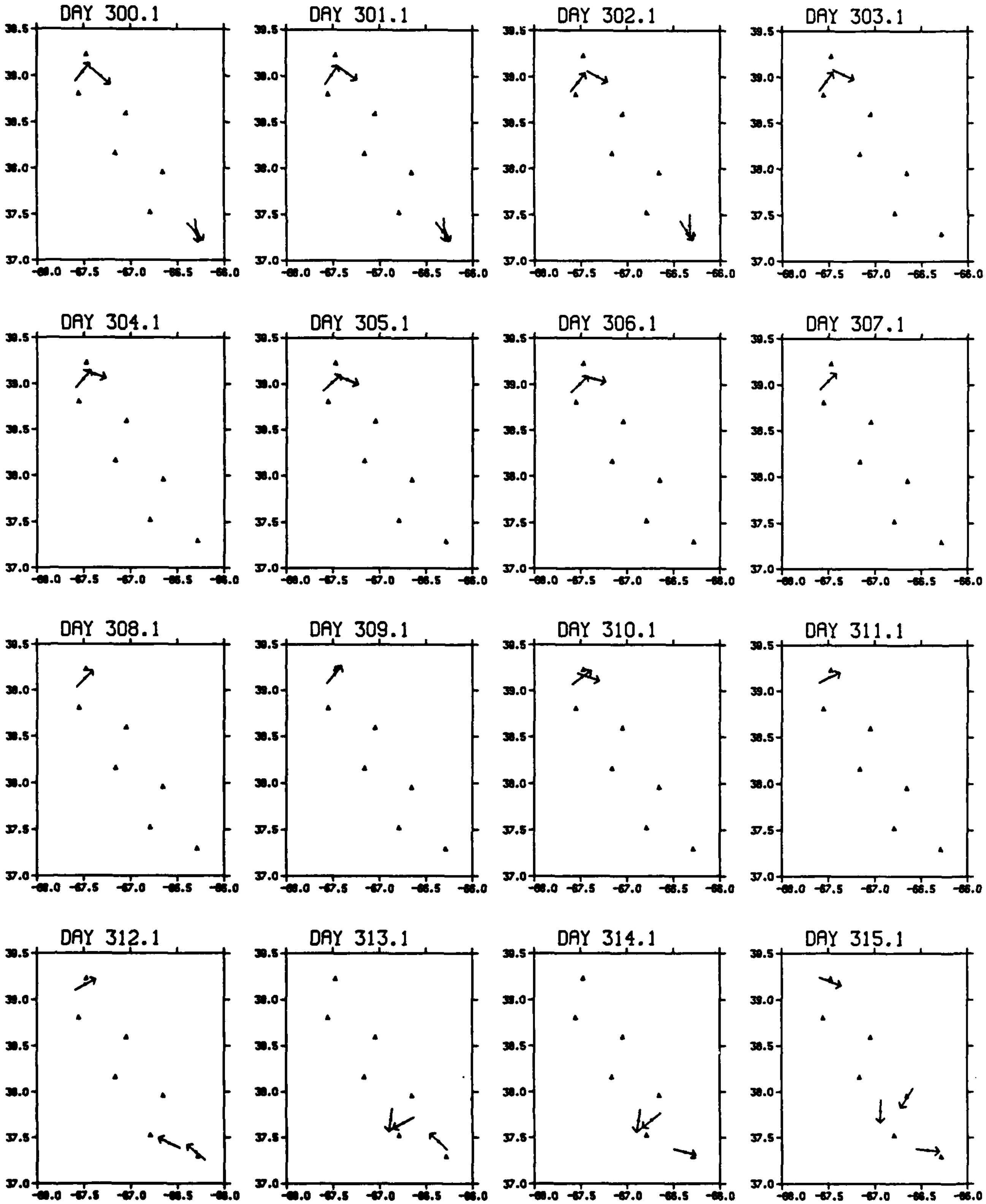

Fig. 12*a*

Fig. 12. IES representation of the Gulf Stream path for the western array for (*a*) days 300 (October 27) to 315 (November 11) and (*b*) days 316 (November 12) to 331 (November 27).

coverage for resolving north-south flow would have been useful for the eastern array.

A meander was observed propagating through the western array during January 1986. Although the arrays were not designed to resolve zonal structure, the southward flowing leg of the meander is seen during days 375–386 (Figure 7*a*) (daily samples are presented for display purposes) and the northward leg of the meander is seen during days 389–398

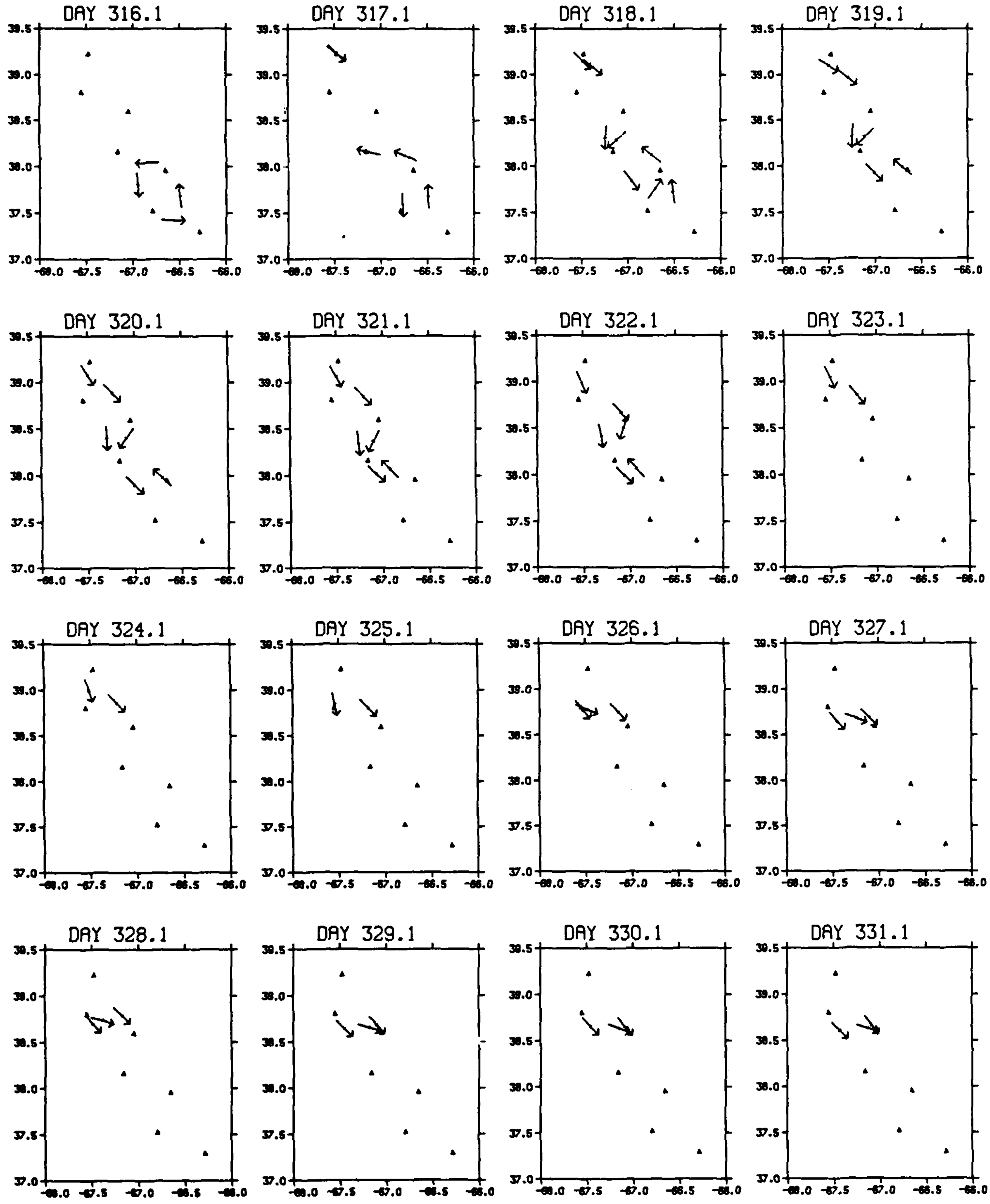

Fig. 12*b*

(Figure 7*b*). One-half meander period is estimated to occur between days 377 and 393. Thus a meander period of 32 days is observed for a wavelength estimated from January IR products to be about 350 km, which corresponds to a propagation speed of about 11 km/day.

Gulf Stream lateral shifting speeds are readily available throughout this data set. An eastward flowing stream traversed the entire eastern array (157 km), from north to south during December in 15 days, yielding a shifting speed of 10.5 km d^{-1}.

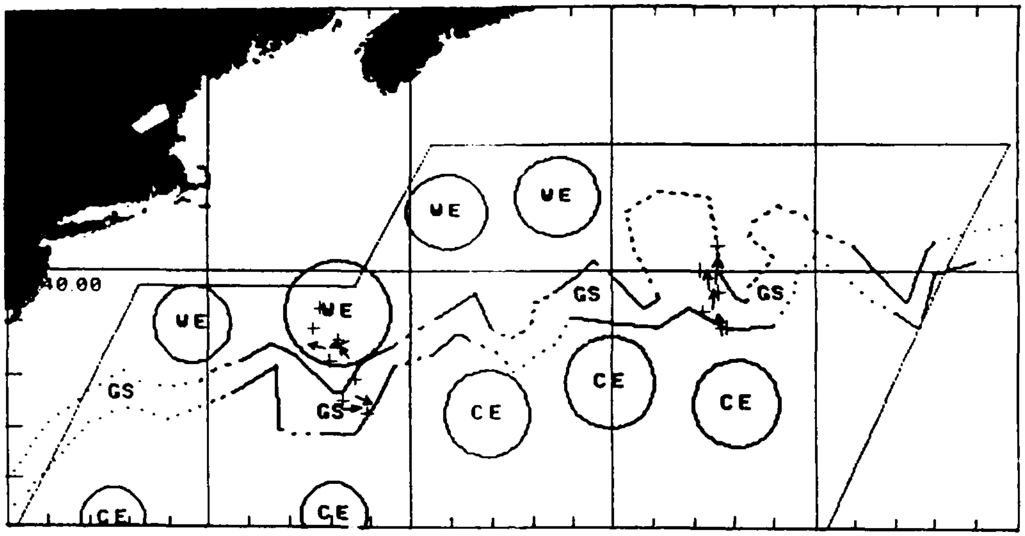

Fig. 13. IES-derived Gulf Stream position and direction superimposed on the April 11 (day 466) GOAP mesoscale analysis.

6. Method Verification

Continuity of stream location and direction is generally good within each array, except for periods when Gulf Stream flow is outside the array limits. To better interpret Gulf Stream features as seen from the IES path analysis and to gain confidence in the technique, IES-derived stream paths are compared with stream paths derived from several other methods.

During August 1985, the temperature field in the REX area was mapped by the Naval Ocean Research and Development Activity (NORDA) over a 6-day period with 341 AXBTs. A nearly cloud-free IR image for this time period is shown in Figure 8*a*. The depth of the 17°C isotherm was related to dynamic height through a regression analysis using hydrographic observations. For this case, Gulf Stream features seen in the dynamic height field closely correspond to the features apparent from the IR image. IES-derived stream position and direction are superimposed on the dynamic height field shown in Figure 8*b*. Excellent agreement with the AXBT-derived dynamic height field is found for both the eastern and western arrays.

During the IES deployment period, NORDA generated a near-real-time (3–7 days) oceanic mesoscale feature map from IR imagery, Geosat altimetry, and XBTs for the REX area [*Lybanon and Crout*, 1987]. This analysis is used in a developmental program (the Geosat Ocean Applications Program, or GOAP) sponsored by the Oceanographer of the Navy to produce near real-time analyses of ocean mesoscale topographies in a NW Atlantic test site (which coincides with the REX region). A map is produced once or twice per week showing the location of the Gulf Stream and warm-core and cold-core rings. Typically, altimetry is used to position features for about 30% of the map and IR imagery is used for about 50% of the map, while the rest of the map is estimated, attempting to maintain feature continuity within this map and with previous maps.

The August GOAP analysis (Figure 8*c*) also shows good agreement with IES-derived Gulf Stream position and direction. Differences in positions of thermal features (such as eddy signatures) between Figures 8*b* and 8*c* are the result of sparser data and averaging in the latter. Since the IES-derived vectors are instantaneous, intercomparisons with GOAP maps are somewhat difficult. Hence it is necessary to examine the time evolution of the IES-derived Gulf Stream position and direction over the period of the corresponding GOAP map. Examples of such intercomparisons are presented in the following paragraphs.

The October 2 (day 275) GOAP representation (Figure 9) portrays a meander and an eddy over the western IES array and a meander through the eastern array. The inverted echo sounder interpretation (Figure 10) for the western array shows a meander in the process of pinching off a warm eddy (day 275), with eddy separation at day 279. This interpretation is consistent with that of the GOAP analysis. The feature evident from the GOAP map over the eastern array is displaced about 30 n. mi (56 km) to the north. Feature description from the 12-day IES record appears to be consistent with the GOAP representation. The time resolution of the IES interpretation clearly has the advantage over the GOAP analysis.

GOAP maps from November 2, 14, and 21 (days 306, 318, and 325) (Figures 11*a*, 11*b* and 11*c*) show a cold eddy in the process of separating from the Gulf Stream over the western array. A cold eddy and the stream are also seen from the IES representation during days 300 to 331 (Figure 12). The IES interpretation can be reconciled with the GOAP analysis interpretation. The right side of the eddy appears at day 312. A complete closed eddy circulation is formed by day 316. The eddy and the stream coalesce between days 317 and 322, which is also apparent in the GOAP analysis of November 21 (Figure 11*c*). Over the eastern array there appears to be an ambiguity between a stream meander and an eddy between November 2 and 14. The IES representation indicates a meander between days 300 and 312, which is also seen in the GOAP interpretation but displaced by over 150 n. mi (278 km) to the west. Agreement between the IES representation and the GOAP map is good for November 14 and 21.

A final example shows a warm eddy coalescing with the Gulf Stream over the western array in the April 11 GOAP analysis (Figure 13). The IES representation of this process is striking (Figure 14); the eddy and the stream are separate from days 460 to 470; the stream appears to be absorbing the eddy from days 471 to 476, forming the southward leg of a meander with the right quadrant of the eddy by day 474; then the meander begins to turn back to the north by day 477;

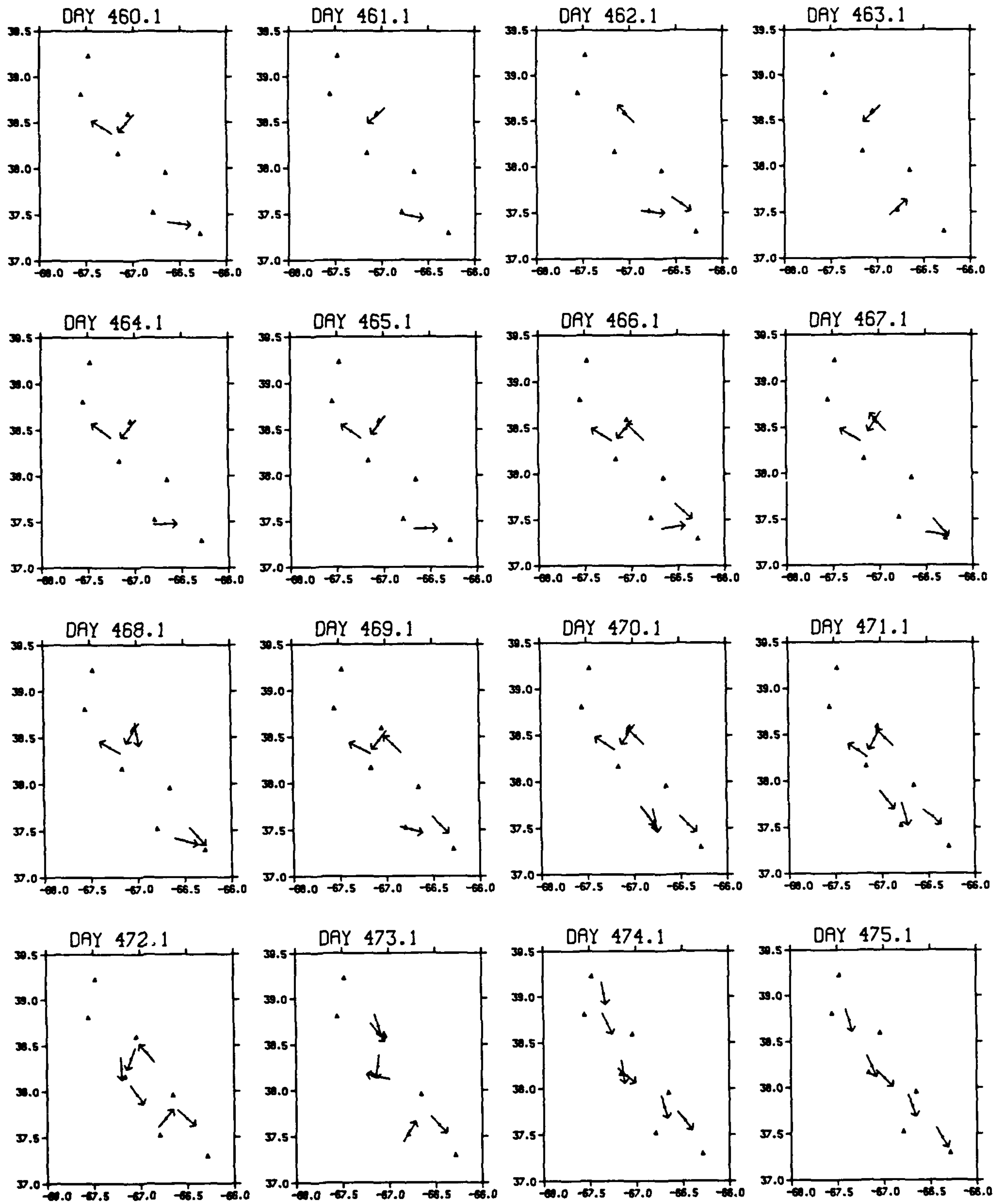

Fig. 14*a*

Fig. 14. IES representation of the Gulf Stream path for the western array for (*a*) days 460 (April 5) to 475 (April 20) and (*b*) days 476 (April 21) to 491 (May 6).

remarkably, a cold eddy forms on day 478 and is seemingly separated by day 481. Over the eastern array, the meander in the GOAP map is seen but displaced about 50 n. mi (93 km) to the east.

IES analyses were compared with 101 GOAP maps. Results are presented in Table 1. In general, IES and GOAP intercomparisons are favorable but are better in the west than in the east.

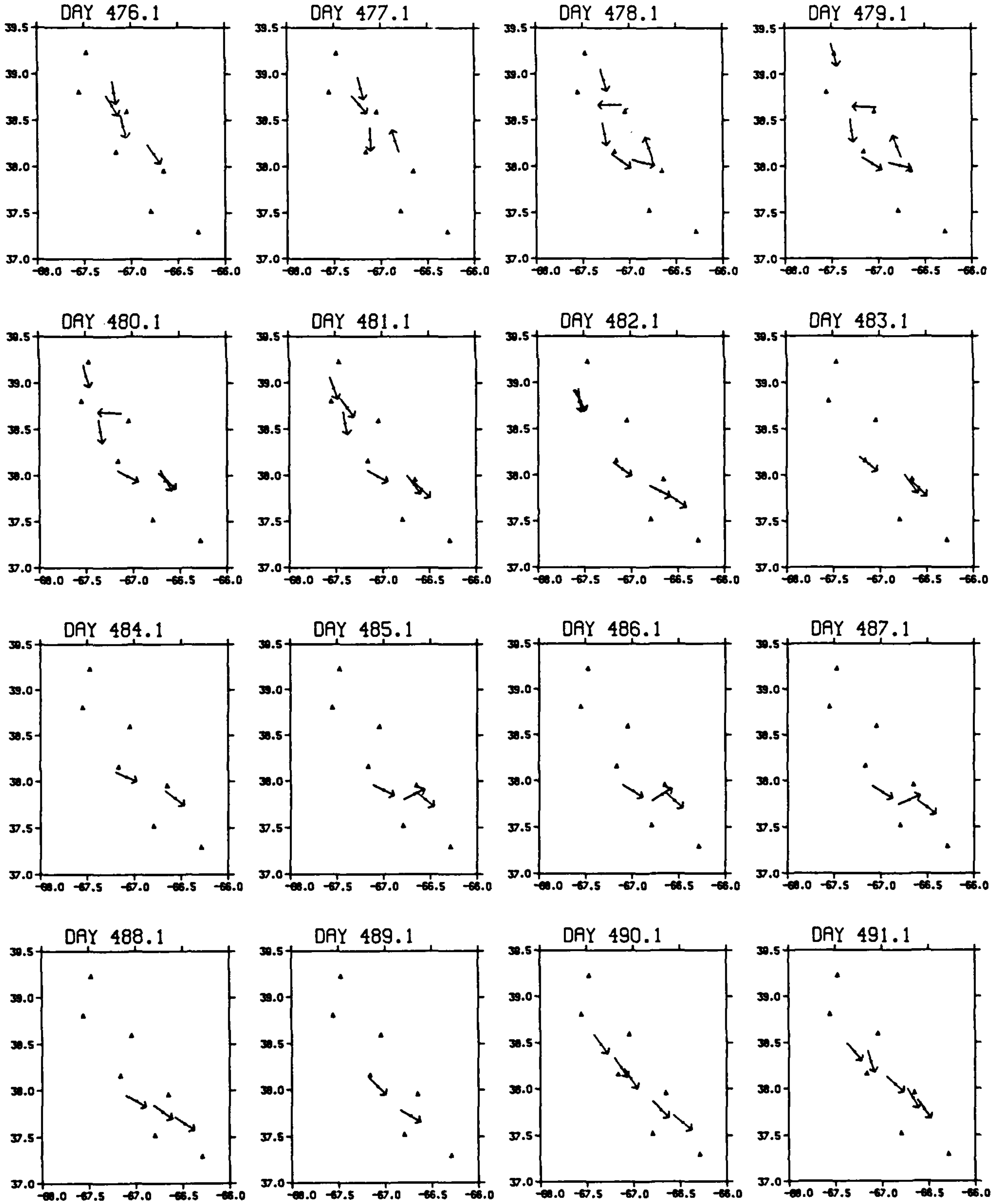

Fig. 14*b*

7. Discussion

The IES description of the Gulf Stream over the western array (67°W) shows that an eastward flowing stream was dominant. However, the stream direction was basically northward at 58°W for most of the 13-month recording period. An eastward flowing stream in the mean is the usually accepted representation in the vicinity of both array locations. Using satellite-tracked drifting buoys, *Richardson* [1983] calculated mean velocities and velocity variances for

TABLE 1. Comparison of GOAP and IES Analyses

	West	East	Total
Good agreement, %	70	31	51
Favorable agreement,* %	13	44	28
Poor agreement, %	17	25	21

*Features displaced.

this region on a 2° × 2° grid. He found that the mean directions over both IES array sites were eastward with the major axis of variance directed east-west or parallel to the mean stream over the western site and north-south or perpendicular to the mean stream over the eastern site, indicating high meander activity over the eastern site. Our data also support the hypothesis that meander amplitude significantly increases to the east of the seamounts [*Fuglister*, 1963; *Warren*, 1963]. In a 5-year survey of the Gulf Stream system and its rings, *Auer* [1987] found that the mean path direction was east-northeast from 75° to 48°W. However, a bump in the mean curve near 56°W was indicative of the more frequent passage of meanders. He also found that upon dividing the ring statistics into 2.5° bands that the mean direction for rings within the 57.5°–55.1° band was northward (014°) and that the mean direction for rings within the 70.0°–67.6° band was westward (270°). Hence eddy translation directions are essentially parallel to average directions determined from the IES data.

Using free-drifting buoys, *Richardson* [1981] stated that the New England Seamounts apparently disrupt the Gulf Stream, resulting in a ring meander over and downstream of the seamounts (a ring meander is a feature that looks like a meander that is in the process of separating from the stream to form a ring yet remains as a semipermanent feature). His data suggested that the Gulf Stream had formed a large, 350-km-diameter ring meander located partially over the seamounts and another meander east of the seamounts. We found evidence for a similar quasi-stationary meander east of the seamounts near 58°W. The IES Gulf Stream path representation is very similar to one of three interpretations of a single historical data set by *Fuglister* [1955] (also shown by *Stommel* [1965, Figure 43]) which shows a single, dominant stream with a basically eastward flow at 67°W and the northward flowing leg of a meander at 58°W. If Fuglister's representation is indeed similar to the Gulf Stream conditions during the IES recording period, then a shift of 1° to the east in the eastern array location would have resulted in the stream's missing the array for most of the recording period. It was fortuitous that the eastern IES array monitored a northward flowing stream at all.

In the IES-derived Gulf Stream vectors we frequently observed probable ring-Stream interactions. In particular, a case in which coalescence of a warm eddy and the Gulf Stream resulted in a cold ring formation during April over the western IES array was also similarly observed by *Richardson* [1981], but in reverse order, during April and May 1977 in this same area. The IES recording of this case, which took place over a period of about 11 days, is the first time such an event has been measured in such detail.

In general, observed eddy activity was much greater over the western array (67°W). Eddies were observed for more than 25% of the recording period for the western array but for less than 5% of the recording period for the eastern array (58°W). *Auer* [1987] also found that the region of greatest ring activity is near 65°W. In this region of high eddy activity, while horizontal coverage is limited for the IES arrays, their discrimination between eddies and the Gulf Stream is significantly better than that provided by the GOAP analyses, which are based largely upon IR imagery.

IR imagery can provide a picture of the surface thermal expression every day or so but is often obscured for days and even weeks by clouds. *Auer* [1987] found that over a 5-year period the Gulf Stream could be observed by satellite IR at 65°W about 90% of the time. This figure ranged from a minimum of 85% of the time during the January–March period to a maximum of 98% of the time during the July–September period. However, Auer found that at 55°W the Gulf Stream was visible only 70% of the time over the entire 5-year period, ranging from 50% of the time during the January–March period to 79% during the July–September period. An IES array, on the other hand, provides us with a continuous record of Gulf Stream position and direction and is not dependent on atmospheric conditions.

North wall (or cold wall or west wall) positions are often used to describe the Gulf Stream. Such descriptions work well where the stream direction does not change more than about 30° from some mean value, as is the case west of about 70°W. They become problematical, however, for a northward flowing stream (where the mean path is eastward), which was the case for more than 20% of the time for the western array and 50% of the time for the eastern array. A Gulf Stream landward surface edge (GSLSE) is more correct in terminology [*Auer*, 1987]; it is not necessarily parallel to the flow field as a north wall classification implies. GSLSE represents the current's edge nearest to the North American continental land mass and is analogous to the north wall in the northwest Atlantic. When analyzing statistics of GSLSE, the orientation of its path relative to longitudinal transects must be considered. If the path is not orthogonal, the standard deviation and ranges will tend to be overestimated, but the mean and extreme positions will be unaffected.

8. SUMMARY AND RECOMMENDATIONS

This interpretation of our IES observations presents evidence for the existence of a quasi-stationary meander near 58°W. This result is consistent with earlier as well as concurrent observations but differs from the view of predominantly eastward propagating meanders throughout the region. IES arrays can accurately monitor Gulf Stream location and direction and can provide descriptions of developing mesoscale features. The ability to monitor the development of mesoscale features at time resolutions of hours over time scales of months to years can greatly enhance our understanding of Gulf Stream dynamics.

Comparison of IES interpretation with the GOAP analyses, which is based on IR interpretation and altimetry, was significantly better at 67°W than at 58°W. Poorer agreement in the east may be associated with larger Gulf Stream meander amplitudes at 58°W than at 67°W and to degraded IR imagery; cloud cover obstructing IR is more extensive east of the New England Seamounts.

IES path analysis information would be a valuable input to mesoscale prediction models. At present, this is practicable only after the fact. Real-time or near-real-time telemetry of IES (and other moored sensors) would significantly enhance Gulf Stream forecasting ability.

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Z. R. Hallock and W. J. Teague, Naval Ocean Research and Development Activity, Stennis Space Center, MS 39529.

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As part of the Naval Ocean Research and Development Activity's Regional Energetics Experiment, 12 inverted echo sounder (IESs) were deployed from June 1985 to July 1986 in two arrays across the historical mean path of the Gulf Stream near 67° W and 58°W, slightly upstream and downstream of the New England Seamount chain. Gulf Stream positions and directions were computed at half-day intervals for adjacent IES pairs. Levels of variability at the two array locations were similar, but the characteristics of the meanders, in terms of propagation and current direction, were quite different. Evidence was found for a quasi-statutory meander near 58°W. Features deduced from IES measurements are compared with concurrent infrared, air-dropped expendable bathythermograph, and Geosat altimetry observations.

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