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Scales of motion in the deep Gulf Stream and across the Continental Rise

by James R. Luyten

ABSTRACT

An array of 15 moorings with 33 current meters was deployed in the deep water across the Continental Rise near 70°W for eight months. The data thus obtained provide the first synoptic view of the large amplitude, long period variability associated with the deep Gulf Stream region, shown here to have meridional scales of 150 km but zonal scales of less than 50 km. These fluctuations are associated with temperature variation of 0.5°C and exhibit a southward phase propagation of 10 cm/sec.

The mean flow south of the 4000 meter isobath is principally meridional with a remarkably short zonal scale, less than 50 km. This regime of small zonal scale flow appears to extend to 36°N (near 70°W) where the generally eastward mean flow dominates. North of the 4000 meter isobath the mean flow is westward and directed along the isobaths. The spatial variability of the statistical properties of the low-frequency variability suggests that the eddy Reynolds stresses are the dominant ageostrophic contribution to the dynamics of the mean flow, doing work on the mean flow over the region between 36°N and the 4000 meter isobath.

1. Introduction

An array of 15 moorings was deployed, as shown in Fig. 1, in the deep water across the Continental Rise near 70°W longitude in the western North Atlantic in order to examine the space-time structure of the low-frequency fluctuation field in the deep water near the Gulf Stream. The data from the moored current meters have provided the first synoptic view of the spatial structure of the large amplitude fluctuations which are characteristic of the deep Gulf Stream (Schmitz, Robinson, and Fuglister, 1970; Schmitz, Luyten, and Sturges, 1975). In this report we shall address a few of the many aspects and implications of these observations, focusing upon the broader inferences as to the scale and statistical character of this flow regime and its possible dynamics.

In the deep water, we find that there are two regimes for both the mean and fluctuation fields, separated nominally by the 4000 meter isobath, which we have designated the upper and lower Rise. In the region to the south of the 4000 m isobath (depth $\geq 4000$ m) the mean flow is principally meridional, characterized

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by a remarkably small, \( \leq 50 \) km zonal scale, (see Fig. 6). The meridional scale is larger, \( \sim 150 \) km. The zonal component of the mean flow over this region is to the east, and appears to be part of an eastward zonal mean flow of appreciable spatial
extent (Worthington, in press; Schmitz, 1976a). This region appears to be dominated by the deep Gulf Stream variability—meridional bursts of flow of $0(40 \text{ cm/sec})$ and some 30 days duration, with essentially the same spatial scales as the mean flow. The bursts appear to become less frequent south of $36^\circ\text{N}$, although we have no clear evidence for a southern boundary to this regime of variability.

To the north of the 4000 meter isobath, which we have designated the upper Rise, the mean flow is directed along the isobaths toward the west. The entire region, extending up to 500 meters, participates in this westward flow. The spatial scales of the flow appear to be controlled by the local topography. The low-frequency variability seems to involve two distinct phenomena. The fluctuation at periods of order 30 days and longer appears to be of a spatial scale comparable to the width of the upper rise, suggesting a meandering and pulsation of the mean flow. In the band between roughly 5 and 20 days there is a characteristic fluctuation of smaller spatial scale making an acute angle with the local topography, associated by Thompson (1971) with topographic Rossby waves. Near the 4000 meter isobath there is a smooth transition between the two regimes.

We have estimated the contribution to the momentum balance of the mean flow by the eddies or low-frequency fluctuations. The “eddy force” per unit mass is found to be of the order of 1 (cm/sec)/day. Over the lower Rise, the eddies are found to do work on the mean flow, while on the upper Rise, the acceleration of the mean flow by the eddies is nearly orthogonal to the mean flow (see Fig. 17). While the possible errors in the estimates are large, we believe that the sign and order of magnitude of the estimates are significant.

That the eddies must play a role in the momentum balance of the zonal mean flow was suggested by Schmitz, Luyten and Sturges (1975). We are extending those conclusions to the meridional flow for which the observed small-scale zonal variability in the eddy field is essential.

2. The data

A total of 32 VACM current meters and 2 M.I.T. T/P recorders were deployed across the Rise in April, 1974 and recovered in December; all but two of these have complete records of velocity and temperature of approximately 240 days duration. Record number 5372 yielded no directional information and record 5292, no temperature. Vector averaged velocities were recorded over half-hourly intervals and processed through the usual W.H.O.I. processing. For the purposes described here these data have been further processed by low-pass filtering in the time domain with a running mean Gaussian filter of 24 hour half-width. This filter removed the contributions from tidal, inertial and higher frequency variability, while passing 95% of the power at periods of 5 days. For convenience, these time series are subsampled once a day.
Figure 2. Distribution of instrumentation on the Rise Array. Solid (dashed) line corresponds to 70°W (≈ 69° 30'W) circles refer to M.I.T. T/P recorders.

The nominal depth of observation was 1000 meters above the ocean floor, with additional instrumentation at 200 meters from the bottom on some moorings. This depth was dictated to some degree by the consideration that the instruments not encounter the strong flow associated with the Gulf Stream. Previous observations indicated that the long period fluctuation field was bottom-intensified, so that a “common” level of observation should be measured relative to the local depth. The distribution of instrumentation along the two meridional lines is shown in Fig. 2. The basic data set is shown in Fig. 3 in an approximately geographically correct
Figure 4. Paths of the 15°C isotherm at 200 meters representing the position of the Gulf Stream.

disposition; for compactness the data from mooring 525, 45 km to the west of Site D (524), have been omitted.

The nominal separation between the moorings was 50 km in the southern sector of the array, gradually extending to 100 km zonally near the northern end.

The meridional focus of these observations was originally dictated by an interest in the interaction of the strong fluctuations under the Stream with the stronger topography on the upper Continental Rise. The existence of the small zonal scales in the lower Rise was unexpected. Thus, unfortunately, the zonal structure of the flow over significantly larger scales remains unexplored. We anticipate that this information may come from moored array experiments currently under way.

One of the objectives of the observational program was to examine the relationship between the deep variability and the meandering of the Stream. Synoptic observations of the position of the Gulf Stream were not possible for the duration of the moored observations. Some tracks of 15°C isotherm at 200 meters depth, T₁₅, were made after the array was set and again in December. These are shown in Fig. 4. An analysis of the intervening period is in progress, although the satellite imagery does not promise an unambiguous view of the Stream's position.

3. Scales of motion

One of the striking features of data presented in Fig. 3 is the appearance of
several distinct events or bursts of flow of some 30 days duration. As we have mentioned in the Introduction, these are typical of the fluctuations observed in the vicinity of the Stream. In this section some of the broader inferences to the scales of the field will be examined. In subsequent sections we shall examine the structure of the mean and fluctuation fields in somewhat greater detail.

Each presentation of the data emphasizes particular features of the data set. Since many of the results from this experiment are qualitatively significant (and unexpected) we are including various presentations of the data. In order to emphasize the long period fluctuations, the time series are filtered using a Gaussian low-pass filter in the time domain with a 10 day half-width. The temporal structure of the meridional flow is emphasized in Fig. 5, which illustrates the visual similarity of the flow across the two meridional sections, separately. In Fig. 6 the same data are

Figure 5. 10-day filtered currents from the Rise Array (north up).

Figure 6. 10-day filtered currents from the Rise Array (east up).
The bursts, which appear along both longitudes, are neither co-incident in time nor similar in orientation. The relatively steady westward flow on the upper Rise is seen to give way to the burst-dominated region to the south. This figure emphasizes the long meridional scale of the flow, particularly the zonal component, penetrating far up the slope. The bursts, which appear along both longitudes, are neither co-incident in time nor similar in orientation. It appears, however, that the same

Figure 7. Array representation of 10-day filtered currents from the Rise Array.
phenomenon is occurring along both longitudes, but that the scale of the motion is of the order of or smaller than the zonal separation, 50 km.

The time series representation emphasizes the longitudinal or transverse similarity between the individual records, while giving little sense of the vector field as a whole. A sequence of “snapshots” shown in Fig. 7 emphasizes the view that although there is no visual similarity between the two meridional sections, the same process is evidently occurring. The bursts are accompanied by temperature variations of the order of 0.5°C at 1000 meters level (~3000 meters depth) shown in Fig. 8. In view of the time scales of these phenomena, and the stability of the θ/S relation in this region, we can only conclude that these fluctuations are associated with displacements of density surfaces of the order of 300 meters, and presumably in approximate geostrophic balance.

The vertical structure of the field is quite simple. The visual similarity shown in Fig. 9 and, indeed, the estimated coherence is large between corresponding velocity components at the two levels from a given mooring, with the upper level attenuated. This particular example is typical of the data set, and in agreement with previous observations. The structure is evidently baroclinic and bottom-intensified. This intensification is a ubiquitous feature of the low frequency variability and appears to continue until 50-100 meters above the bottom.

In order to avoid some possible confusion with the term baroclinic, we observe that a vertical modal decomposition (linear problem), over a sloping bottom, does not allow a mode which is independent of depth. Indeed, the bottom-intensified topographic wave is the barotropic mode which becomes depth independent only as the horizontal scale of the motion becomes large with respect to the penetration depth (L >> NH/f; Rhines, 1970). Our particular observation is that the bursts have vertical shear and an associated density variability. Recent velocity profiles
taken in the vicinity of the Gulf Stream suggest that these structures are confined to the region below the base of the thermocline (Saunders and Luyten, 1976).

4. Mean field properties

A time average over the duration of the record gives estimates of the mean properties of the field: the mean flow and fluctuation field energy and correlation. With a field such as we have described above, in which the most energetic events have long time scales and occur intermittently, the question of the representativeness of these estimates is not trivial. It is conventional to assume that the population from which these records were drawn is stationary, in which case the record averages will contain, in addition to the statistical mean, contributions from the variance at periods equal to twice the record length and longer. In the absence of significantly longer time series, two alternatives present themselves. We can look for consistency between different records taken at the same location. Such comparisons are presented below. We must remember, however, that the similarity between records separated by several years may be strongly dependent upon the particular location, or may be a coincidence.

An alternative approach has been undertaken by Schmitz (1976b) through assembling long but gappy time series from various nearby locations, which we shall refer to as global averaging. This procedure naturally involves spatial and temporal averages.
The basic record averages from the Rise array, summarized in Table 1, form the basis for the discussion below. Table 2 contains the detailed comparison between the record averages of the Rise array and the historical and globally averaged data.

The observed mean flow along the Continental Rise can be separated nominally by the 4000 meter isobath into two regimes as shown in Fig. 10. We do not attribute any particular dynamical significance (at present) to this depth. The flow in the region shallower than 4000 meters, the upper Rise, is directed along the isobaths to the west. The entire upper Rise appears to participate in this flow, and the flow appears to be guided by the local topography, although there must be a lower limit on the scale of topography to which the mean field can respond. The effects of the canyons which cut across the Rise are unknown.

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<td>37.9</td>
<td>-9.0</td>
</tr>
<tr>
<td>3471</td>
<td>39°50'N 70°41'W</td>
<td>776</td>
<td></td>
<td>104</td>
<td>-6.5</td>
<td>1.6</td>
<td>22.4</td>
<td>38.7</td>
<td>2.2</td>
<td>-7.3</td>
</tr>
<tr>
<td>3511</td>
<td>39°37'N 71°15'W</td>
<td>2052</td>
<td></td>
<td>111</td>
<td>-5.1</td>
<td>-0.4</td>
<td>13.1</td>
<td>61.9</td>
<td>4.6</td>
<td>10.8</td>
</tr>
<tr>
<td>3461</td>
<td>39°36'N 70°58'W</td>
<td>2163</td>
<td></td>
<td>86</td>
<td>-7.3</td>
<td>-0.1</td>
<td>26.7</td>
<td>117.9</td>
<td>6.9</td>
<td>-5.9</td>
</tr>
</tbody>
</table>

† Global averages are used with permission from W. J. Schmitz, Jr.

Although we have not traced this flow along the upper Rise, there are isolated observations of a generally westward flow in this region, extending from the Grand Banks to Cape Hatteras (Richardson, 1976). Webster (1968) has reported a westward flow at Site D (39°10'N, 70°W; mooring 524 here) at all levels, decreasing with increasing depth. The observations above 200 meters were from surface moorings, so that the magnitude of the flow is suspect (Gould and Sambuco, 1975). Our estimates of the mean flow in this vicinity are in agreement with Webster (1968) to within 1 cm/sec.
The mean flow in the region deeper than 4000 meters is more complicated than that along the upper Rise. This region, the lower Rise, exhibits a remarkably small zonal scale. The separation between the two meridional sections of the Rise array is 50 km. Evidently the spatial structure in zonal direction has not been resolved, suggesting a zonal scale even smaller than 50 km. When these data are taken together with the data from a previous array (moorings 357-368), we see that this entire region may be characterized by a small zonal scale.

The meridional scale of the mean field is significantly longer, of the order of 100 km and perhaps longer since we do not know the extent of this flow regime to the south.

The zonal component of flow seems to be a broad mean flow corresponding to the flow along the upper Rise. Schmitz (1976b) has observed this to reach a maximum near Site J (36° N). The westward component of flow near the Caryn Seamount, mooring 364, may have been induced by the strong local topography. The meridional flow contains the small zonal scale, apparently induced by the large amplitude bursts, of comparable spatial scales. The regime of meridional flow of
small zonal scale is then associated with the region of the bursts. These bursts appear to be frequent near 37°N, and occasionally may extend as far south as 34°N, 62°W. Indeed the large velocities observed by Swallow (1971) at 4000 meters depth in the *Aries* data, Area C (34°N, 62°W) are similar to the deep Gulf Stream bursts discussed above. Swallow (personal communication, 1975) has suggested that the *Aries* data may indicate a correspondingly small zonal scale. As these events become less frequent, their effect upon the mean flow may become less significant.

The mean properties of the fluctuation field, defined by removing the individual means from the data, are summarized in Table 1. The components of the Reynolds stress tensor \( \left( \frac{u'^2}{v'^2} \right) \) are represented in Fig. 11, in diagonalized form, by the invariant (under rotation) major and minor axes of the principal ellipse, and its orientation. Along this direction, there is no correlation (Fofonoff, 1968) between the two orthogonal components of the transformed velocity.

As with the mean flow, the structure of the fluctuation field can be separated by
the 4000 meter isobath into two regimes. On the upper Rise, the region shallower than 4000 meters depth, the principal ellipses are quite elongated, generally making an angle of less than ±30° to the local topography. Thompson (1971) and Thompson and Luyten (1976) have suggested an explanation for this. The bottom slope \((\approx 5 \times 10^{-3} \text{ in this region})\) may effectively prevent across-slope motions of periods longer than 20 days while permitting topographically controlled oscillations with periods of the order of 5-15 days. The variability of the longer periods may be associated with a meandering and pulsation of the mean flow directed along the isobaths. This mechanism is under investigation. The slope region, moorings 346-351, has been discussed by Schmitz (1974).

The fluctuation field on the lower Rise appears more spatially variable than on the upper Rise. The apparent constraint on the across-slope motion is lifted on the lower rise. The ellipses are less elongated suggesting a more isotropic fluctuation field. There appear to be systematic differences in the fluctuation field between the two meridional sections which we shall discuss below since they represent Reynolds stresses gradients associated with the eddy field.

The vertical structure of the fluctuation field appears to be bottom intensified, at least between the 1000 and 200 meter levels above the bottom. This can be seen in both Table 1 and Fig. 11. This bottom intensification can be seen in both regions of the Rise, and indeed appears to be a ubiquitous feature of the eddy field (Gould, Schmitz and Wunsch, 1974).

The vertical structure of the motion appears to have several common features throughout the region. We mentioned above the observations of Webster (1968) in which he found the mean flow to decrease with increasing depth. This is borne out in the Rise data near Site D, although the effect is not pronounced.

On the lower Rise, where the mean flow arises from the burst structure, the mean flow carries the bottom intensified structure of the basic variability. There is in addition an apparent tendency for the deep mean flow to turn to the left with increasing depth. It is the fact that nearly every mooring exhibits this effect that encourages us to explain it, despite its indeterminant statistical significance.

Bryden (1975) has shown that such a turning of the flow with height can be related to the horizontal advection of density via the thermal equation under the assumptions of a geostrophic and hydrostatic balance. This horizontal advection of density can be balanced by either a vertical advection of density \((w \sim 3 \times 10^{-4} \text{ cm/sec})\) or a temporal change in density at seasonal or longer time scales. This latter possibility receives some support from the seasonal displacement of the slope front (Wright, in press) and the mean Gulf stream (Fuglister, 1975; Worthington, in press).

We must, before leaving the discussion of the mean properties of the field, return to the question of the representativeness of the estimates. A direct comparison of the means from the Rise array data and from long historical time series near Site D
Figure 12. 1-day filtered currents from moorings along 70°W.
and individual shorter records is made in Table 2. In the vicinity of Site D, the 240-day estimates are evidently within 1.5 cm/sec for the mean flow, and 20 cm$^2$/sec$^2$ for the fluctuation field.

The stability of the estimates of the mean flow near the 4000 meter isobath [3261 vs. 5302, 3681 vs. 5313] are remarkable although these records are significantly more energetic than along the upper Rise. The agreement between the means from 3261 and 5302 is perhaps fortuitous since 3261 contains a single energetic event, which gives energies almost twice those from 5302. Evidently the mean along the upper Rise is well-occupied, and we suspect dynamically separable from the fluctuation field.

Along the lower Rise the character of the bursts appears to determine the mean flow. This is a region in which the bursts, while intermittent, appear frequently. The time between bursts is not significantly different from the duration. It is remarkable that all of the data taken on the lower Rise along 70°W have shown bursts of the same essential character—a strong northward flow, as shown in Fig. 12. While the precise magnitude of the mean flow and fluctuation field statistics is uncertain, the sign and order of magnitude are unambiguous. The 70°W data set is entirely consistent. There is no reason to suspect that the estimates obtained from the sections along 69° 30’W are less representative than those along 70°W. Thus we have no reason to reject the existence of the small zonal scales for the mean flow in this region.

We are not able as yet to suggest a southern boundary for this flow regime. Data from Site J (36°N, 70° 30’W; Table 2) suggest that the deep Gulf Stream bursts appear here, although considerably less often. As we have noted above, Swallow (personal communication) has suggested that a Gulf Stream burst was observed in the *Aries* data (Swallow, 1971) at 34°N, 62°W.

The occurrence of these phenomena is not confined to the extreme western region of the Gulf Stream. A series of moored current meter observations, shown in Fig. 13, made during 1972 across the tail of the Grand Banks of Newfoundland, along 50°W, shows a spatial structure remarkably similar to the observations near 70°W (compare Figs. 7 and 13). Only a single section was occupied so that no zonal structure can be inferred. The data set is of only two months duration, encompassing only a single burst so that little statistical information can be obtained. Data taken near the Kelvin Seamount (65°W) suggest a similar degree of variability, although the records were only a month long (Vastano and Warren, in press).

5. Phase propagation

Although the mean properties of the field seem to be separable into two regimes, an examination of the time series data suggests a southward phase propagation throughout the array. This can be seen most clearly in the temperature variations
along both meridional sections, although it is evident in the velocity data as well—Fig. 8. Associating various features in the temperature or velocity series yields phase velocities of 8-15 cm/sec to the south, particularly pronounced during the first two months. A complete statistical analysis of this phase propagation and its implications will be presented in a subsequent paper.

Under the assumption that the underlying field is statistically homogeneous, isotropic and horizontally nondivergent, one can construct an objective analysis of the streamfunction (Bretherton, Davis and Fandry, 1976). Such an analysis is essentially a weighted linear interpolation in space for each time interval, for which the weights are chosen to reproduce the prescribed statistics. The statistical correlation functions, computed from the data, are prescribed.

Of primary importance in the analysis is the spatial scale, defined by the first zero-crossing of the transverse correlation function. A value of 85 km for this scale was estimated from the data although the maps are not sensitive to the precise value—several values were used with only minor changes in the maps. The maps shown below are suggestive and are presented principally to quantify the southward phase propagation, not to give a complete statistical analysis. The objective analysis and mapping were performed by Fofonoff (personal communication) from the low-passed data at two-data intervals from the 1000 meter level.

A plot of the streamfunction along north-south sections vs. time, shown in Fig. 14, shows the southward phase propagation clearly—the phase lines show a persistent tilt, corresponding to a phase-velocity of 12 cm/sec. This tilt is particularly clear during the first half of the record, extending the entire length of the section.

Figure 13. Array representation of 1 day filtered currents from the Grand Banks Array, along 50°W.
Figure 14. Objective analysis of streamfunction from 10-day filtered currents. The center of each frame is at 38°N, 69° 45'W, extending from 36°N to 40°N, and 71°W to 68° 30'W. A frame is plotted every two days, starting in the lower lefthand corner on 28 April, 1974.
The individual streamfunction maps, shown in Fig. 15, show a regular progression of eddies southward through the array.

It should be clear from what we have said in previous sections that the data set appears to be neither homogeneous nor isotropic in its statistics. This analysis, particularly the presence of eddy-like closed circulations, should only be considered to be suggestive. The time a given parcel of fluid remains in an eddy can be estimated using the streamfunction maps—it was found to be short compared with the transit time for the eddy. This confirms the interpretation of a propagation of phase. Indeed the analysis requires the streamfunction to tend asymptotically to zero where there is no data so that jet-like behavior can only be synthesized from two closed circulations.
There is no discernible phase propagation in the zonal direction, although with only two longitudes this would be difficult to observe. There is no suggestion in the original velocity or temperature data of a visual similarity between the two meridional sets of data, let alone a correlation.

It is common to find a westward phase propagation in the open ocean. Rhines (1975) has shown that westward phase propagation, common in linear $\beta$-plane models (Rossby wave dynamics) of ocean circulation persists in nonlinear models and that it may be a ubiquitous feature of open-ocean variability. The strong bottom topography of the Continental Rise, however, must dominate the $\beta$-effect. Linear models imply a southward propagation (topographic Rossby waves) which may persist when the dynamics are no longer those of linear topographic waves.

6. Momentum balance and dynamics

It is known that the large scale ocean circulation at mid-latitudes is in approximate geostrophic balance. Indeed much of our present understanding of the deep ocean circulation has been based upon the assumption of geostrophy, and certainly the major ocean currents are associated with horizontal density gradients of the correct order of magnitude. The mesoscale eddy observed in the MODE-I experiment has been shown to be in geostrophical balance to within observational error (Swallow, personal communication; Bryden, 1975). It is also known that a geostrophic balance gives no insight into the dynamics of the flow, i.e., there is no way to assess the role played by the eddy scale motions. Limitations on our present ability to observe the ocean preclude detailed momentum, energy and vorticity budgets. However, we may be able to indicate terms that must be present, although they are small with respect to the basic geostrophic balance.

It has been suggested that the eddies or low-frequency fluctuation field may play a dominant role in the dynamics of the ocean circulation, in a manner perhaps analogous to the mid-latitude atmospheric dynamics (Stommel, 1966).

The direct influence of the low-frequency variability upon the mean circulation can be assessed by estimating the relative contribution of the Reynolds stress gradients to the horizontal momentum equation for the mean flow $\bar{v} = (\bar{u},\bar{v})$

\[
(\bar{v} \cdot \nabla) \bar{u} - f \bar{v} + \frac{1}{\rho} \bar{p}_x = -\left\{ \frac{\partial}{\partial x} (\bar{u}'^2) + \frac{\partial}{\partial y} (\bar{u}' \bar{v}') + \frac{\partial}{\partial z} (\bar{u}' \bar{w}') \right\}
\]

\[
(\bar{v} \cdot \nabla) \bar{v} + f \bar{u} + \frac{1}{\rho} \bar{p}_y = -\left\{ \frac{\partial}{\partial x} (\bar{u}' \bar{v}') + \frac{\partial}{\partial y} (\bar{v}'^2) + \frac{\partial}{\partial z} (\bar{u}' \bar{w}') \right\}.
\]

The corresponding equation for the kinetic energy of the mean flow is

\[
(\bar{v} \cdot \nabla) (K_M) + \frac{1}{\rho} (\bar{v} \cdot \nabla \bar{p}) + \left\{ \bar{u} \left[ \frac{\partial}{\partial x} (\bar{u}'^2) + \frac{\partial}{\partial y} (\bar{u}' \bar{v}') + \frac{\partial}{\partial z} (\bar{u}' \bar{w}') \right] \right\}
\]
From a horizontal array such as the Rise array, we have no way of estimating the vertical gradients $\frac{\partial}{\partial z} (u'w', v'w')$. Similarly, from this observation period we have no method for determining the mean pressure gradients. We can only assume that one exists of sufficient magnitude to finally balance these momentum equations. What we can estimate are the mean flow, its self advection and contributions to the horizontal gradients of the Reynolds stress from the low-frequency variability.

Schmitz, Luyten and Sturges (1975) have reported large meridional changes at 4000 m depth along 70°W in the structure of the eddy field. They suggested that the observed gradients play a role in supporting the general circulation, particularly the deep zonal recirculation postulated by Worthington (in press), and observed along the lower Rise.

Our observations are not inconsistent with these calculations, but rather suggest that the zonal gradients may play an equally important role for the meridional flow.

The Reynolds stress gradients appearing in the above momentum budget are to be computed at a fixed level. As we have discussed above, however, the eddy field is bottom intensified so that in the presence of the sloping bottom, there is an apparent spatially induced meridional gradient at a given level. Within the context of this data set, it is not possible to separate the two effects, bottom intensification and meridional variation, unambiguously. We have performed the calculations in two ways: taking a fixed level relation to the bottom (1000 m), and separating the data into depth intervals. The conclusions from the two calculations are essentially the same.

There are marked differences in the behavior of the eddy statistics between the two meridional sections, summarized in Fig. 16 for the three depth intervals, 2000, 3000, 4000 meters. The eddy kinetic energy, $K_E$, shows no systematic difference between the two sections, both exhibiting a nearly linear decrease with increasing latitude. The two components, however, show an opposite (complementary) structure. Progressing up the slope, the zonal eddy energy, $u'^2$, decreases slowly, showing a systematic difference between the two sections, then is consistently higher along the 70°W section than along 69° 30’W ($\partial u'^2/\partial x < 0$). On the other hand, the meridional eddy energy, $v'^2$, is more sharply attenuated by progressing up-slope with the eastern section dominant. The sharp attenuation of the meridional eddy energy near 38°N is undoubtedly related to the increasing bottom slope. The transverse momentum flux, $u'v'$, appears to be consistently positive near 36°N, vanishes near 37°N and is negative beyond 39°N. Between 37°N and 39°N, the momentum flux is positive along the 70°W section while along the eastern section it takes negative values.

The eddy contributions to the momentum budget, the acceleration of the mean
Figure 16. Meridional distribution of low frequency fluctuation field from (nominally) 4000(•), 3000(×) and 2000(+) meters depth. Data points from eastern section are circled.

Flow due to the Reynolds stresses, a force per unit mass, have been estimated by fitting planes in least square to each set of data. The values are assigned to the median position, as shown in Fig. 17, together with the interpolated mean flow.

Although numerous estimates have been shown for the eddy acceleration terms, we believe that a single estimate of each component is appropriate for the region to the north of 37°N. This is supported by the consistency between the various estimates.

One panel shows the depth sorted data, as in Fig. 16, for the 2000, 3000, 4000 meter depths. The other panel shows the estimates made from each set for neighboring values at a common depth. These estimates vary quantitatively, although the qualitative picture is unchanged. The relative scales for the eddy force and mean flow in Fig. 17 have been chosen so that if a given eddy force were unbalanced for five days, it would generate a mean flow of comparable magnitude.

Over the region of the lower Rise, the eddy force dominates over the mean flow advections by an order of magnitude, and generally does work on the mean flow (force × velocity > 0).

Along the upper Rise, the eddy forces become comparable with the advection of the mean flow, although not balanced by it, and generally extract energy from the mean flow (force × velocity ≈ 0).

The magnitude of the eddy force per unit mass, order 1 (cm/sec) per day, is small compared with the Coriolis acceleration (0(10(cm/sec)/day)) for these flows,
although they represent a significant contribution to the energy budgets if not balanced by the pressure work terms, or vertical transfers. Indeed the eddy forces appear to be the important ageostrophic contributions to the momentum balance for the mean flow. Their particular dynamical significance is not yet known.

7. Conclusion

The data from the Rise array represents the first synoptic view of the field which we recognize to be typical of the deep water near the Gulf Stream. This field is dominated by bursts of some 30 days duration with an amplitude of order 40 cm/sec. These bursts are principally meridional, with a vertical structure that is bottom-intensified. The bursts are accompanied by displacements of density surfaces (isotherms) of the order of 300 meters at the 1000 meter level. The spatial structure of the field is highly anisotropic with a meridional scale of $\sim 150$ km and a zonal scale of less than 50 km. This regime is evident in the region to the south of the 4000 meter isobath. In depths shallower than 4000 meters, the upper continental rise, a different and less energetic flow regime is evident. The burst field is evidently not stationary; the bursts occur at apparently random times, the frequency of occurrence decreasing with increasing distance from the Stream.

The mean flow and perturbation statistics are estimated from the 240 day record
averages, giving mean flows that appear to be stable to within 1.5 cm/sec and perturbation kinetic energy that appears to be stable to within 20 cm²/sec².

Along the upper Rise (depths shallower than 4000 meters) the mean flow is westward having the spatial scales of the Rise itself with variability evidently induced by the local bottom topography. On the lower Rise (water depths greater than 4000 meters) the mean flow, reflecting the structure of the bursts, is principally meridional of order 5 cm/sec, with a meridional scale of ~ 150 km and a zonal scale of less than 50 km. This spatial structure, which does not appear to be imposed by the local bottom topography, is consistent with previous observations in the deep Gulf Stream region.

From the data available, we have made a necessarily crude estimate of the effects of the eddies upon the mean flow arising from the horizontal Reynolds stresses. We find that the eddies do work upon the mean flow in the lower Rise-deep Gulf Stream region, in substantial agreement with Schmitz, Luyten and Sturges (1975). On the upper Rise, the acceleration of the mean field by the eddies is nearly orthogonal to the mean flow so that little or no work is done.

The small zonal scale in the lower Rise region suggests that there are significant zonal variations in the eddy field with corresponding variations in the eddy force.

These variations in the eddy field are of sufficient magnitude to give rise to a force per unit mass of order 1 cm/sec per day, suggesting that the eddy terms are the leading geostrophic terms in the momentum energy and vorticity balances for the mean flow.

Our knowledge of the kinematics of this field, and its possible relation to the Gulf Stream itself in the upper levels, is still so primitive that we are unable to identify the processes responsible for this field. The evidently baroclinic low-frequency fluctuations are not inconsistent with geostrophic turbulence (Charney, 1974; Rhines, 1975) although this again says nothing about the process or the role of the eddies in the dynamics.

As yet, we know little about the southern extent of the burst regime, with its associated (induced?) small zonal scale mean flow. Without further observations in this region, we cannot assess the significance of small zonal scale to the general circulation. The burst regime appears to be a common feature of the deep Gulf Stream region, suggesting that this is the deep Stream. If there were a coherent deep extension of the Gulf Stream, as suggested by Fuglister (1963) and Robinson, Luyten and Fuglister (1974), it would be nearly completely masked by the deep eddy field.

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