On the eddy statistics in a ring-rich area: A hypothesis of bimodal structure

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ABSTRACT

A hypothesis is introduced in constructing the statistics of an eddy field, which distinguishes Gulf Stream rings as a separate anomalous feature from the mesoscale eddy field. Analysis of XBT sections between New York City and Bermuda with rings removed indicates that the thermocline deepens toward the Gulf Stream from Bermuda and the r.m.s. displacement of the 15°C isotherm is 50 m or less. Despite proximity to the Gulf Stream this baroclinic amplitude is not larger than those found farther south. Temporal and spatial scales of the eddy field appear to be also very similar to mid-ocean scales. Geographical distribution of rings is suggested as the cause of the rapid northward increase of eddy potential energy found by Dantzler (1977).

1. Introduction

Recently, expendable bathythermograph (XBT) data have become increasingly valuable in identifying the presence of eddies in the world ocean (Swallow, 1976). In the North Atlantic Ocean the extensiveness of the historical XBT data makes it even possible to look into the geographical variation of the eddy field (Dantzler, 1977; henceforth referred as D) which is an important clue to the causes of mid-ocean eddies (Richman, Wunsch, and Hogg, 1977). At the same time Lai and Richardson (1977a) (henceforth referred as LR) extended Parker's (1971) work on ring distribution making use of recent data, and successfully described the movements of rings in the western Sargasso Sea.

The previous analyses, D and LR, concern anomalies primarily, but have to define mean fields first with respect to which anomalies can be sought. Therefore the estimates of anomalies strongly depend upon how the mean fields are defined. Examination of the previous results shows that in the western Sargasso Sea their descriptions of the mean field differ substantially. According to D, the mean depth of the 15°C isotherm (the main thermocline) monotonically rises north from Bermuda by about 300 m over 400 km. The Gulf Stream appears as a broad current

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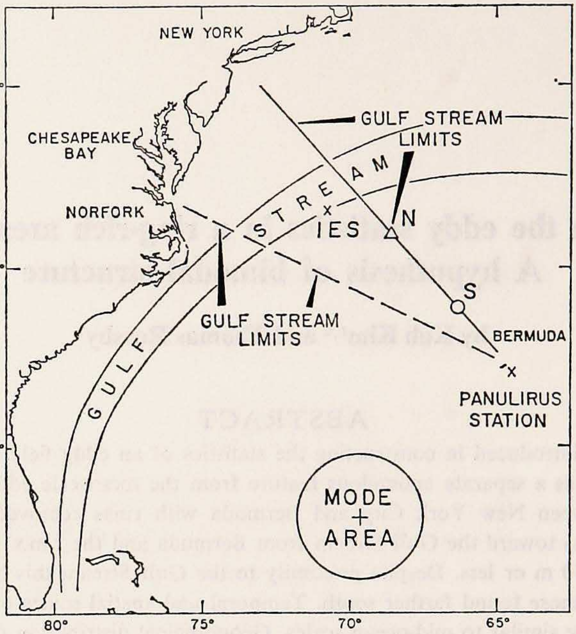

Figure 1. Geographical distribution of source data. NAVOCEANO XBT sections were repeated 118 times between New York City and Bermuda and 18 times between Norfolk and Bermuda. There were 4 hydrographic sections taken on ATLANTIS approximately 3 months apart between Chesapeake Bay and Bermuda in 1932. Panulirus station is located south of Bermuda and the center of MODE is 28N, 69°40′W.

and the center of the subtropical gyre is located near 30N, 75W. On the other hand, LR shows the deepening of the main thermocline to the north from Bermuda as well as the regions of high temperature gradient associated with the Gulf Stream. The subtropical gyre has a center near 34N, 72W. The mean field defined in LR seems to be consistent with historical observations (Iselin, 1936), but that in D does not.

In estimates of anomalies D and LR also show some differences. In D the r.m.s. displacement of the 15°C isotherm increases rapidly towards the Gulf Stream; it varies from 41 m at 29N to 171 m at 35N along 69W. Statistics in Lai and Richardson (1977b) are not intended to look at the mesoscale eddy field, but are nevertheless very useful. After the removal of extreme anomalies mainly due to the core of rings, the r.m.s. temperature fluctuation at 700 m depth is 0.8°C at 28N and 0.86°C at 34N along 69W. With the vertical gradient of temperature of 1.0°C/50 m in the main thermocline LR's estimate is consistent with that of D in the south, but they differ by a factor of four in the north.

In this paper we identify rings as the cause of the discrepancy between D and LR. Furthermore, we propose a hypothesis of bimodal structure of anomalies which requires a complete separation of ring data in constructing eddy statistics. The result

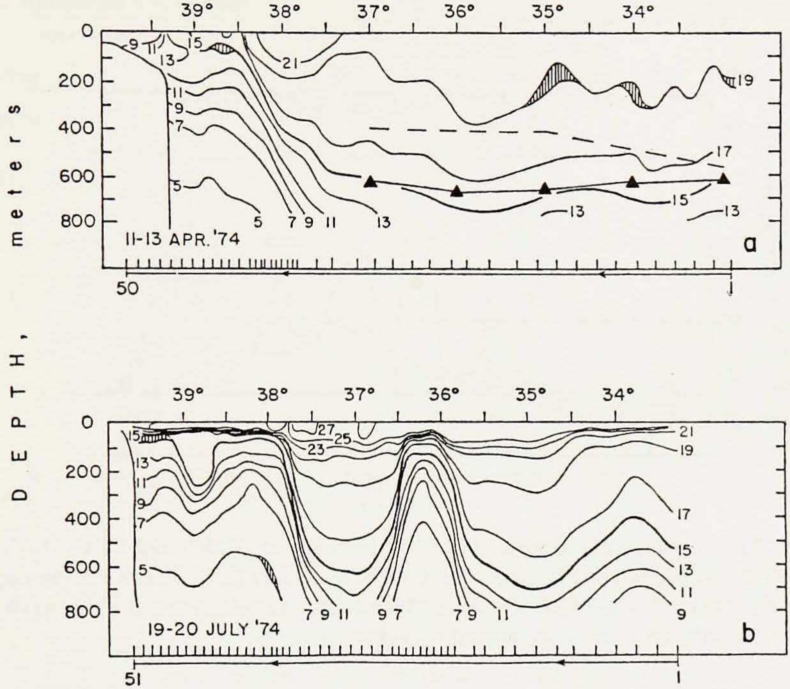

Figure 2. Examples of synoptic NAVOCEANO sections. (a) is absent of ring and shows a peak-to-peak fluctuation of 100 m. Solid and broken lines are the mean depths of the 15°C isotherm found in the present analysis and by Dantzler (1977) respectively. Note that the solid line deepens toward the Gulf Stream, while the broken one shoals. In (b) two rings cause a very large displacement of isotherm depths. The extent of the Gulf Stream meander can be seen in Fig. 1.

based upon this hypothesis indicates little geographical variation of the r.m.s. displacement of the 15°C isotherm in the mesoscale field in contrast to the rapid increase shown in D.

2. Data

The source of data was the series of XBT sections between New York City and Bermuda (Fig. 1) reported in the Gulf Stream Monthly Summary by the U.S. Naval Oceanographic Office (NAVOCEANO). Variabilities are first examined in spatial and temporal structures, and then synthesized in terms of a frequency distribution.

Synoptic Section. Examples of synoptic sections (Fig. 2) illustrate the three main ingredients of variability: meandering of the Gulf Stream, rings and mesoscale fluctuations. As the Gulf Stream meanders, its position varies between 36N and 38°30′N (Fig. 1). The core of a ring (Fig. 2b) can be easily identified as the vertical

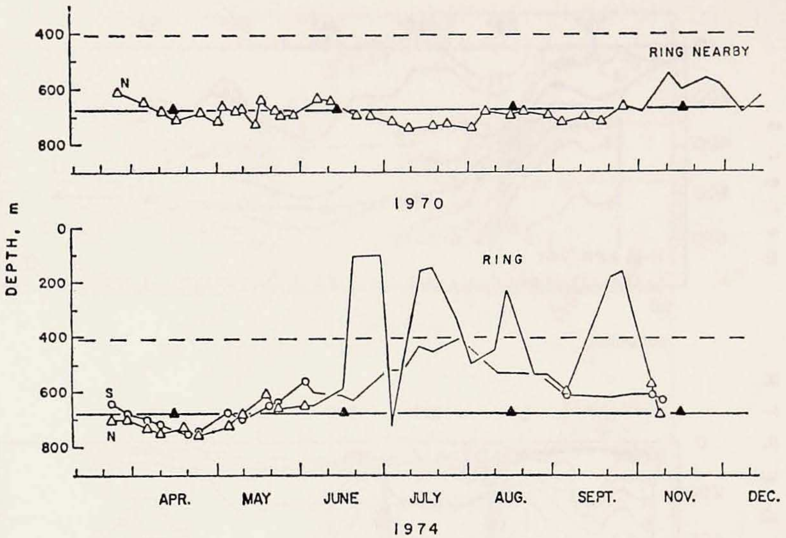

Figure 3. Time series of the depth of the 15°C isotherm at N(36°) and S(34°N) whose locations are shown in Figure 1. During 1970, except for a short period, there was no ring around N and the record shows typical mesoscale fluctuations. The 1974 series by contrast reveal a huge, rapid variation which is associated with rings.

displacement of isotherms larger than 150 m following past studies (Parker, 1971; LR). The center of a ring usually has a displacement of 500 m (Table 1). Also the mesoscale fluctuation of 100 m as a peak-to-peak amplitude is very apparent in Figure 2a. There is, of course, the question of distinguishing between the mesoscale field and the skirts of rings. For the NAVOCEANO sections it was possible to resolve this problem by examining the time series of sections. Rings usually move slowly enough to appear in several consecutive sections. However, for historical data where most observations are random and sparse this kind of identification is virtually impossible except for the core of rings such as was done in LR.

Time Series. Low frequency variation of the thermocline topography is of primary interest and time series of the depth of the 15°C isotherm complement synoptic sections. The sampling every 6 to 8 days is adequate for this purpose. Specifically we examine the series from two locations (36N, 68°15′W) and (34N, 66°10′W) approximately, which are denoted by N and S in Figure 1. As examples, the 1970 and 1974 records are shown in Figure 3.

During 1970 and 1971 six rings passed the section (Table 1). But their effect is not apparent in the series N except for a brief period near the end of 1970 when a ring was close to N. Still a mesoscale variation having a peak-to-peak displacement on the order of 100 m is present throughout the record. The 1973 and 1974 series are markedly different. Rings caused a huge variation on the order of 500 m as they

Table 1. Anomalies due to rings.

Year	Date	Approximate Latitude of Maximum Anomaly	Depth of 15°C (m)
1970	June 7	36°30′	70
	October 25	36°27′	110
1971	April 30	35°17′	170
	July 23	35°00′	170
	August 29	33°57′	260*
	September 17	36°33′	180
1973	July 20	34°10′	180
	August 12	36°25′	180
	August 31	35°55′	130
	December 1	35°12′	550*
1974	June 20	36°00′	330
	July 14	33°50′	110

* Rings centered east of the section.

moved in and out of the section. The time scale of the mesoscale variation is weeks to months, which is comparable to those found south of the present study area (Richman, Wunsch and Hogg, 1977; Schroeder and Stommel, 1969). Inverted Echo Sounder (IES) data sampled hourly in the present study area (Figure 4; see Figure 1 for the position of the IES) indicate short term variations including tides, but their amplitude is small enough to be neglected. It is encouraging that this data set provides a similar range of variation and time scale of the mesoscale field. The records from 1970 and the first half of 1974 records suggest the presence of long term variation with a scale of two months or more, and hence sections during a given season may not represent independent events as far as the low-frequency variation is concerned.

3. Hypothesis of bimodal structure

The preceding examination of the synoptic sections and time series strongly suggests that there is a distinct difference in the range of the depth variation of isotherms between rings and the mesoscale field. The frequency distribution of the depth of the

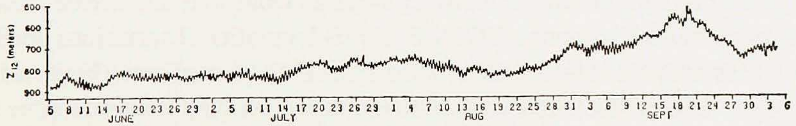

Figure 4. Time series of Inverted Echo Sounder data sampled hourly at position IES in Figure 1 (from Watts). This separate and independent data set also yields a peak-to-peak variation of 100 m and time scales longer than a few days of the mesoscale field as found in Figure 3.

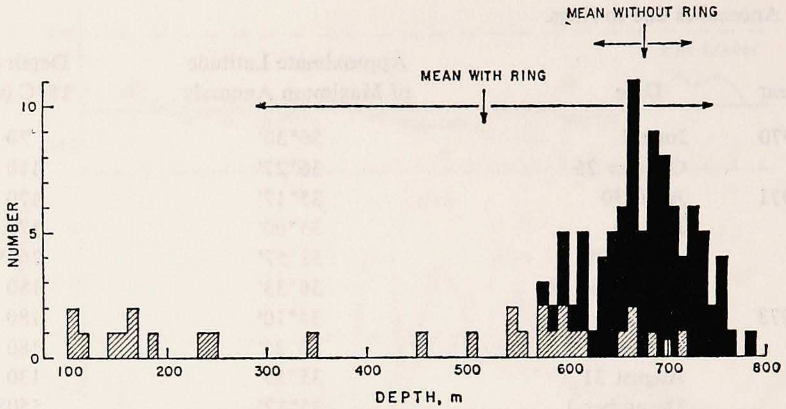

Figure 5. Frequency distribution constructed from the time series at N. Shaded part is the data associated with rings. Note the wide range of variation of ring data, which reflects a spatial structure of rings. The distribution is approximately Gaussian between 500 and 800 m. Arrows are scales of the mean and standard deviation with and without rings. The entire distribution is strongly nonGaussian due to the contribution from rings and the statistics with rings are constructed for the purpose of comparison rather than for their own value. The shallow mean depth and large standard deviation correspond to the statistical results of Dantzler (1977).

15°C isotherm in Figure 5 summarizes the local variability of amplitude, which is characterized by two main features: (1) the distribution is approximately Gaussian between 500 and 800 m, but (2) it has a long tail toward the shallow depth associated with rings which makes the total distribution strongly nonGaussian. The nature of this distribution raises a serious question whether sensible statistics, one for rings and the other for the mesoscale field, are needed in order to describe the variability. This is not a question of pure statistics, instead the resolution of this problem requires a certain physical model which is consistent with observations. The following review summarizes relevant observational evidence.

1) It is well-known that rings are products of extreme Gulf Stream meanders (Fuglister, 1972; Parker, 1971), not a local process in the Sargasso Sea. After moving a distance of thousands of kilometers over a period of 2-3 years, most rings eventually coalesce with the Gulf Stream off Florida before they decay significantly and become indistinguishable from the mesoscale field (LR; Cheney and Richardson, 1976). Some 3-4 months observations made soon after the ring formation showed a faster sinking (decay) rate (Fuglister, 1972; Parker, 1971), but longer observations indicate a very slow rate after the initial stage (Cheney and Richardson, 1976; Cheney, Gemmill, Shank, Richardson and Webb, 1976). This genesis and decay of rings should be described as a discrete, single entity of cold anomaly. However, the success of this descrip-

tion depends upon how the mean field is defined. The dynamical origin of the mesoscale field is uncertain as yet.

2) During the survey period 10 rings were observed in the NAVOCEANO sections. For seven of them the depths of the 15°C isotherm at their center were shallower than 200 m. Two rings were approaching the section when observed and only one ring recorded 330 m as the 15°C isotherm depth at its center. Individual sections of course, show a continuous variation of amplitude over a wide range, but *this reflects the structure of rings rather than a broad distribution of peak amplitude.*

Based upon these observations, it is hypothesized that rings and the mesoscale field are quite distinct and should be separated in constructing eddy statistics. The physical significance of this hypothesis will become evident later when interpreting the statistical results. Here it is worth pointing out the difference between this hypothesis and the simple displacement criterion. The minimum displacement criterion such as adopted by Parker (1971) and LR is very useful in identifying rings since it is expected that only the core of the rings can have such an extraordinary displacement. On the other hand, this kind of criterion is not adequate to make a distinction between the mesoscale field and the skirts of rings. The proposed hypothesis aims at removal of all ring data, skirts as well as core, from the data base.

The following procedure for removing ring data from the NAVOCEANO sections considers the fact that rings usually move westward crossing the section at least once. (1) By examining individual sections, rings with a very large displacement such as the one in Figure 2c are identified. (2) Sections before and after the one with rings identified in (1) usually contain the same rings with a lesser amplitude. Until the trend of the extreme amplitude in individual sections reverses, the features are identified as rings. In (1) and (2) data taken within 150 km from the extreme are removed.

4. Statistical analyses and results

Statistics are constructed with and without rings for 1974 when the two rings passed through the section, one around 36N and the other around 34N. Exclusive of rings, the mean depth deepens toward the Gulf Stream (Fig. 6a), and the r.m.s. displacement is about 50 m (Fig. 6b) and does not show any spatial trend. On the other hand, inclusion of ring data in the statistics yields very different results: the mean depth is shallower by as much as 140 m and the r.m.s. displacement increased by a factor of two to four. Typical rings have a diameter of 200 km and the effect of rings is apparent in the entire section. Similarity between the two displacement curves suggests a possibility of residual ring effect in the statistics without rings, probably because the skirts of rings, which were near the section, could not be entirely removed. It can be seen clearly in Figures 3 and 5 that the shallow mean

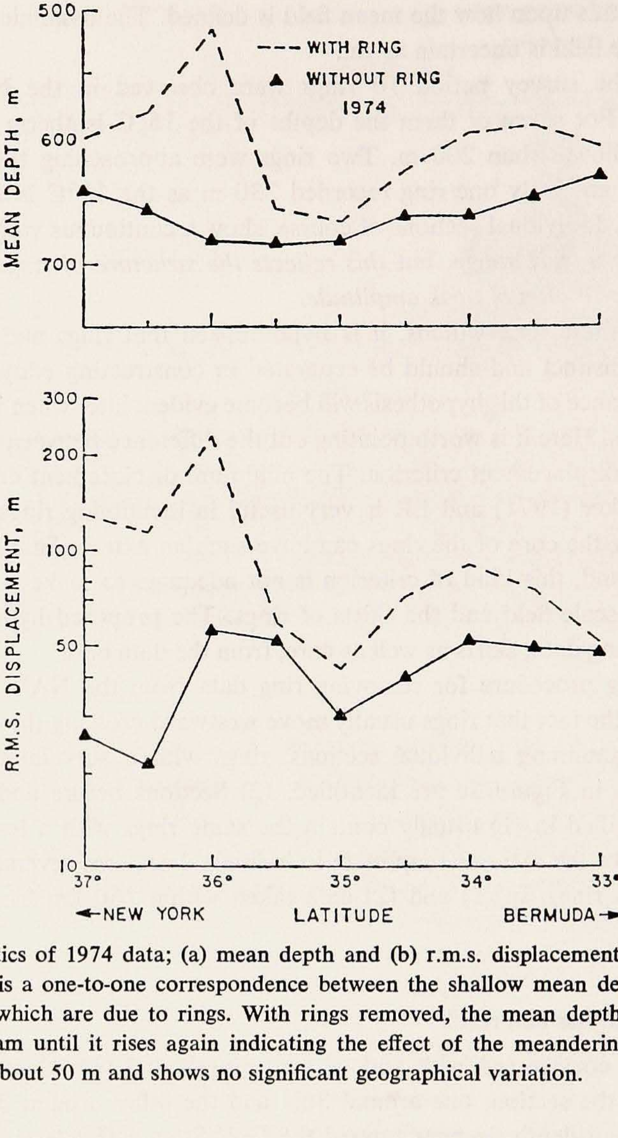

Figure 6. Statistics of 1974 data; (a) mean depth and (b) r.m.s. displacement of the 15°C isotherm. There is a one-to-one correspondence between the shallow mean depth and the large displacement which are due to rings. With rings removed, the mean depth deepens towards the Gulf Stream until it rises again indicating the effect of the meandering. The r.m.s. displacement is about 50 m and shows no significant geographical variation.

depth, due to rings, does not have any counterpart in the ocean. Therefore, the physical significance of this shallow mean depth and large r.m.s. displacement is very uncertain. This simple comparison of two statistics demonstrates that the separation hypothesis is crucial in constructing eddy statistics.

Since the time series indicate a possibility of long-term variations (Fig. 3), it would be worth examining year-to-year variation. Table 2 shows annual statistics without rings at 36N. For reference it also includes statistics with rings for 1973 and 1974. The r.m.s. displacement varies between 35 and 56 m and the mean depth

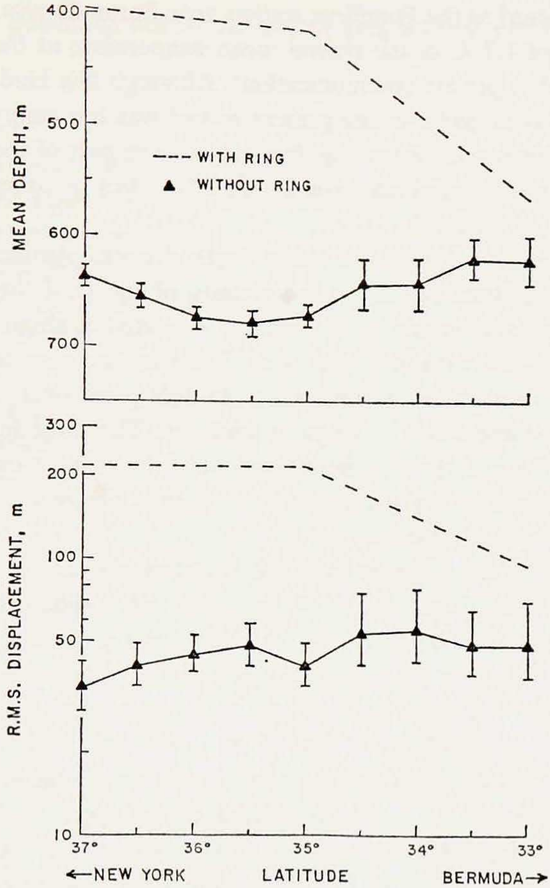

Figure 7. Statistics of the entire record with ring removed in comparison with Dantzler's results (1977). The basic patterns are the same as the 1974 statistics in Figure 6. The mean field is consistent with the historical knowledge. Surprisingly there is no evidence of increase of the baroclinic eddy activity despite the proximity to the Gulf Stream compared with statistics from the Panulirus station and the MODE area.

changes as much as 36 m from one year to another. This seems to indicate that in addition to the mesoscale variation of periods less than half a year there may exist a very low-frequency variability with periods longer than one year. It is interesting

Table 2. Year-to-year variation at 36N.

Year	1970	1971	1973	1973(R)*	1974	1974(R)*
Number of samples	32	26	9	18	14	29
Mean depth (m)	690	654	667	583	681	516
Displacement (m)	35	40	56	204	56	227

* Rings included in statistics.

that an 18-year record at the Panulirus station near Bermuda also indicates a peak-to-peak variation of 1.7°C of the annual mean temperature at the depth of 600 m (Elizabeth Schroeder, private communication). Although this kind of variation is of great interest, it was judged that the present record was too gappy and short to remove the trend. This is specifically true for the southern part of the section since the 1970 and 1971 sections terminate around 35N. Statistics of complete data without rings are presented in Figure 7.

Within 95% confidence limit the mean depth deepens significantly from 33 to 36N, then begins to shoal rapidly in the vicinity of the Gulf Stream. Considering that at the Panulirus station the 15°C isotherm is located at about 600 m, the deepening is quite consistent with historical data. The shoaling near the Gulf Stream is due to the meandering motion which extends to 36N occasionally. The meandering has essentially the same effect as rings in statistics. The most interesting result is that the "ring-free" r.m.s. displacement is about 50 m at most over the entire section and does not indicate any significant trend despite the general notion that eddy activity should increase toward the Gulf Stream.

The present results are different from the statistics obtained from other analyses of historical XBT data. According to D, the mean depth shoals, not deepens, from Bermuda toward the Gulf Stream (Fig. 7a), and the r.m.s. displacement increases dramatically (Fig. 7b). To some extent the cause of this discrepancy can be explained in terms of procedure of data analysis and the geographical distribution of rings. First we will discuss a possibility of two biases in the data base: one is a sampling problem in the vertical direction and the other in the horizontal space. (1) Vertically about 90% of historical XBT data is limited to the upper 450 m (LR). In the shallow XBT data, depth readings of the 15°C isotherm are artificially limited to the XBT's depth range despite the fact that in the absence of rings the isotherm lies deeper than 450 m. Therefore any mesoscale variation of the 15°C isotherm is practically precluded. Combination of this data with deeper XBT data with a termination depth of 750 m would include some mesoscale fluctuations, but the bias due to the majority of data is inevitable and appears to be very serious as far as eddy statistics are concerned. (2) Horizontally area-averaged statistics could also be biased because of the dense sampling in and around rings as can be seen in Figure 2b.

Aside from the preceding problems of data base there is a physical reason why the statistics in D should be different from the present results. In D no distinction was made between rings and the mesoscale fluctuation, so that shallower mean depth and larger r.m.s. displacement are qualitatively consistent with the 1974 statistics with rings included. The remaining question concerns the amount of ring effects. However this cannot be answered properly until the biases are removed. As for the trends, it is natural that the r.m.s. displacement in D increases to the north, since the observed distribution of rings (Fig. 6 in LR) suggests an increasingly high probability of ring distribution toward the Gulf Stream. However, the true probability cannot be reliably quantified due to the lack of geographical uniformity in historical data.

5. Discussion

A statistical analysis based upon the hypothesis which requires a separation between rings and the mesoscale field shows that there is little or no tendency of the r.m.s. displacement of the mesoscale field to increase toward the Gulf Stream in the vicinity of 70W. The r.m.s. displacement in the study area is 50 m or less, which is quite comparable to that observed at the Panulirus station (32°10′N, 64°30′W) (Kim, 1975) and in the MODE area (28N, 69°40′W) (LR). During the MODE period a spatial average yields an r.m.s. displacement of about 28 m (Kim, 1975 and it is believed that this is an underestimate due to the short record. A similar analysis for 18 XBT sections taken between Norfolk and Bermuda during 1972 (ship tracks are shown in Fig. 1), also gives an r.m.s. displacement of 50 m or less. As early as 1932, Iselin (1936) took a series of hydrographic sections between the Chesapeake Bay and Bermuda and reported a striking flatness of the isotherm depths, except for a slight upward trend toward Bermuda which was observed throughout the sections. These XBT and hydrographic observations are entirely consistent with results of the present statistical analysis.

There are physical justifications for the separation hypothesis. Frequently the r.m.s. displacement in combination with the Brunt-Väisälä frequency was used to estimate an eddy potential energy as in D. Since in the study area the Brunt-Väisälä frequency varies much less than the r.m.s. displacement on isotherm surfaces, the eddy potential energy is directly proportional to the squared displacement. The eddy potential energy has a physical significance only when considered in combination with the mean potential energy (Lorenz, 1960). In energetics this also means that the kinetic energy is also presumed to be made of both mean and eddy parts. In the absence of the hypothesis the shoaling of the main thermocline suggests a rather strong, eastward mean current between the Gulf Stream and Bermuda which is clearly not the case.

In view of some numerical and theoretical models (Holland and Lin, 1975a and b; Robinson, Harrison, Mintz and Semtner, 1977; Flierl, 1977) which suggest a strong spatial inhomogeneity in the eddy field, the proposed hypothesis results in a fundamentally different geographical variation of the eddy field. If the Gulf Stream and/or its return current is indeed a source of mid-ocean eddies, this study suggests that its effect should be nearly barotropic, which is transparent in the baroclinic (density) field. This can be tested only through direct measurements of currents. Available current data (Swallow, 1971; Freeland, Rhines and Rossby, 1975; Richman, Wunsch and Hogg, 1977) seems to indicate an increase associated with the Gulf Stream and its return current in the vicinity of 70W. But the pronounced effects of topography (Rhines, 1971; Freeland, Rhines and Rossby, 1975) obscure the significance of this geographical variation. Alternatively it is possible that its baroclinic effect is confined to the vicinity of the Gulf Stream system with an e-folding distance of the radius of deformation. Rings are themselves extraordinary, anomalous features in the area, but their effect on the ambient eddy field is not apparent statistically. Since statistics represent only the average field of dynamics with motions of all scales, we cannot rule out the possibility of individual dynamical processes such as the radiation from rings (Flierl, 1977). However, the absence of any significant spatial trend in the r.m.s. displacement of the 15°C isotherm suggests strongly that in the vicinity of 70W the dynamics are probably simpler, yet more discretely structured, than the models indicate.

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