Decay of a Shoaling Gulf Stream Cyclonic Ring

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ABSTRACT

An entrainment and diffusion model has been applied to successive observations of a decaying Gulf Stream cyclonic ring to investigate changes in the streamline pattern as the ring moved from deep water onto Blake Plateau. Entrainment of water into the ring core is the dominant feature in each field of streamlines. The decay process measured in terms of the time required to replace the ring volume indicates an approximately linear decrease of renewal time as the ring moves into shallow water.

1. Introduction

A report of cold water anomalies in the Sargasso Sea by Iselin (1936) is perhaps the earliest reference to eddies formed by meanders of the Gulf Stream. Fuglister (1972) suggested the term "ring" be applied to these special features, while Parker (1971) produced a generalized description of rings based on a survey of Woods Hole Oceanographic Institution bathythermograph records.

The decay processes in cyclonic rings have been the subject of numerous studies. Rooth (1967) and Molinari (1970) have suggested mixing along isopycnal surfaces and advection of surrounding waters are important factors in ring decay. Lambert (1974) found that variations in profiles of dissolved oxygen supported these ideas and the small-scale layering could be caused by diffusion and the advection of Sargasso Sea Water into the eddy core. Cheney and Richardson (1976) also reported layers of Sargasso Sea Water inside the ring and described the decay of a cyclonic Gulf Stream ring as a radial shrinking of the cold core. Entrainment and diffusion processes were modeled by Schmitz and Vastano (1975); the results were streamline patterns for selected diffusivity coefficients which showed entrainment to be the dominant decay mechanism for short-term temporal changes in the ring.

2. Data and model

In 1971 a ring located by infrared imagery was repeatedly observed by satellite and shipboard measurements (Richardson *et al.*, 1973). Cruises to the ring, conducted over the 14-month period before the ring coalesced with the Gulf Stream off Florida, resulted in the data base used by Cheney and Richardson (1974) to describe the decay process of a cyclonic ring. This long-term series of observations of a single ring presented an opportunity to investigate changes which might have occurred in entrainment as the ring aged. The model developed by Schmitz and Vastano (1975) was applied to these data for that purpose. A brief description of the data analysis and the model follows.

Station data were obtained for the five cruises, but the spatial distribution was not sufficient to develop temperature fields from contoured horizontal sections through the ring. Cheney and Richardson (1974) combined the station data with XBT's to form diametral ring sections of temperature. For our purposes, these fields were digitized to obtain spatial distribution of temperature for each cruise. There was a marked degree of asymmetry in the ring structure, which was most pronounced in more shallow water. The remaining steps in preparing data for the model followed those presented by Schmitz and Vastano (1975).

Least-squares regression analysis was used to solve for the coefficients of the streamfunction

$$\psi = r^2 z(A_0 + A_1 r + A_2 z + A_3 r^2 + A_4 rz + A_5 z^2)(z+D),$$

where D is the average depth of water corresponding to the average temperature field of the two cruises considered. Since the ring moves from deep water into

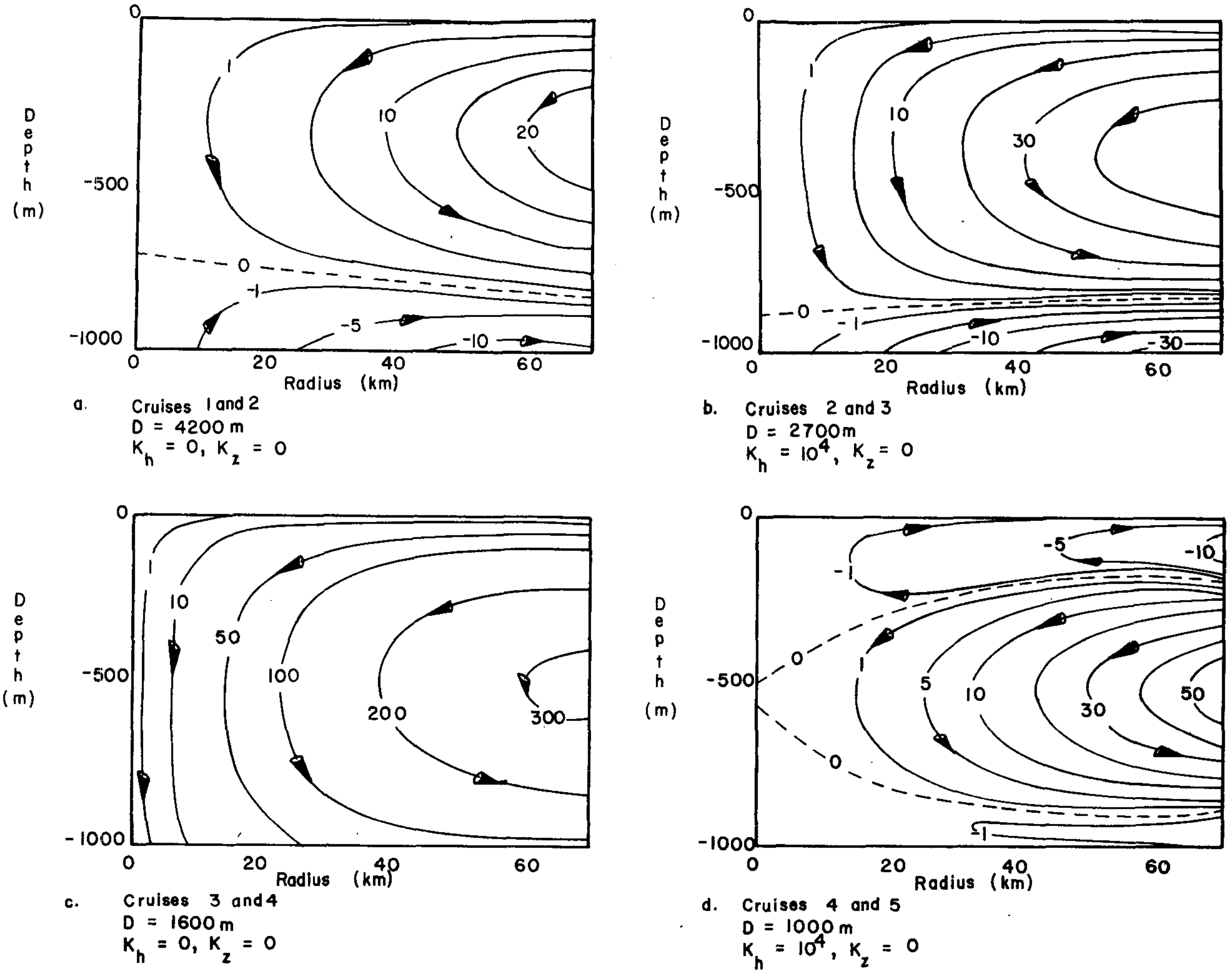

FIG. 1. Streamfunction (10^8 cm^3 s^{-1}) patterns for cruises 1–5 taken in sequential pairs. Eddy diffusivity coefficients are expressed in cm^2 s^{-1}.

shallow water, the term $(z+D)$ was included in the polynomial approximation of the streamfunction to allow some response to the changing depth of water. The addition of this term provides a boundary condition ($\psi=0$) at the bottom that augments similar conditions at the ring center ($r=0$) and surface ($z=0$).

The five cruises are those selected by Cheney and Richardson to study the decay of ring potential energy. Each cruise found the ring over a significant bathymetric gradient. Cruise 1 (May 1971) begins the sequence with the ring center at the foot of the continental slope and moving onto the Blake-Bahama Outer Ridge at a depth of 5200 m. The ring center for cruise 2 (October 1971) is at 3200 m immediately adjacent to the Blake Plateau. For cruise 3 (January 1972) the ring is centered on Blake Spur at a depth of 2200 m and cruises 4 (February 1972) and 5 (April 1972) have the ring centered at a depth of 1000 m on the Plateau.

Although the analysis assumes a symmetric, circular ring and implies that it is embedded in a uniform oceanic environment, the application has been made to provide an initial estimate of the effect of the topographic interaction on the ring dynamics in a complex physical situation. The cyclonic ring clearly undergoes a strong interaction with the Blake Plateau. This is most evident in the large subsidence of isotherms that occurred between cruises 3 and 4. Also, the ring was quite close to the Gulf Stream during cruises 4 and 5. Thus the dynamic interaction of the ring exceeds the model's implied restrictions and the results can only qualitatively be used to approximate the rate at which its decay was proceeding in terms of exchange with its environment.

3. Results

Figs. 1a–1d, shows the numerically derived streamline patterns for the decaying ring. All stages show entrainment of water into the ring core from without ($r=70$ km) at depths more shallow than 400 m. Fig. 1a shows two cells which model an entrainment regime yielding a renewal of the volume above 1000 m in 21.7 years. Fig. 1b is similar in structure with an increase flow that renews the volume in 8.9 years. The streamlines for cruises 3 and 4 (Fig. 1c) produce a renewal time of 2.4 years. During the time spanning cruises 1–3, the ring was moving into shallow water. The average depths for cruises (1–2), (2–3) and (3–4) are 4200, 2700 and 1600 m, respectively. Fig. 1d shows the streamline pattern for cruises 4 and 5 developed for an average depth (D) of 1000 m. The entire volume of the prototype is present in this representation and three cells model the exchange of water with the environment. The renewal time in this case is 11.4 years.

4. Discussion

The parametric study was completed for horizontal eddy diffusivity coefficients (K_h) of 0 and 10^4 cm^2 s^{-1} and vertical eddy diffusivity coefficients (K_z) of 0, 1 and 10 cm^2 s^{-1}. The advective regime ($K_h=0$, $K_z=0$) was not very different from those which included diffusion processes; indeed, in cases (1–2) and (3–4), the advective flow produced the smallest error estimate while $K_h=10^4$ cm^2 s^{-1} and $K_z=0$ represent the remaining cases.

In describing the decay process in the ring, Cheney and Richardson (1976) suggested the bottom layers of the ring may have been lost as the ring moved from deep to shallow water, with further decay caused by the formation of a bottom frictional layer and interaction with the Gulf Stream off Florida. In viewing the streamline patterns for the ring moving from deep water to shallow water, it is interesting to note the migration of the zero streamline downward (Figs. 1a and 1b) and out of the ring (Fig. 1c) indicating a change in the flow at depths greater than 1000 m as the ring was affected by the shoaling bottom. During the period from cruise 3 to 4, the ring moved onto Blake Plateau. Fig. 1d shows circulation cells above and below the cell at the main thermocline level which could imply the additional decay mechanisms of bottom friction and Gulf Stream interaction. The relation between the renewal time for the first three cases (21.7, 8.9 and 2.4 years) and average depths (4200, 2700 and 1600 m) can be approximated linearly on the basis of three points indicating a decrease in life expectancy over the 10-month period of shoaling (Fig. 2). During the period of time from cruise 3 to 4, the ring moved westward and onto the Blake Plateau with the depth shoaling by an approximate factor of 2. Conservation of potential vorticity would imply that the relative vorticity of the ring increased during the transition. Although little is known about the interplay of physical mechanisms in shoaling, after reaching the Plateau the ring had lost approximately half of its kinetic energy, available potential energy and reduced energy (Cheney and Richardson, 1974). Such changes are qualitatively supported by the decrease in life expectancy calculated in this work.

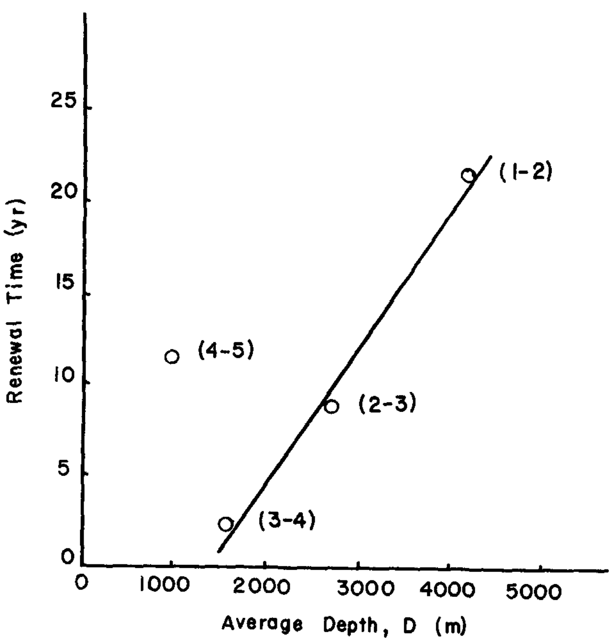

FIG. 2. Renewal time versus average depth for the four cases shown in Figs. 1a–1d.

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