Separation of Warm-Core Rings in the Gulf of Mexico

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ABSTRACT

The separation of anticyclonic rings is studied using a 12-level primitive equation numerical model of the western North Atlantic. The "Gulf Stream Formation Region" model is based on the Bryan-Co-Semtner code, and uses 1/4 degree horizontal resolution. The eastern boundary of the model, near the mid-Atlantic Ridge, is forced by a "pumps and baffles" region to have the appropriate temperature and salinity structure, vertical shear, and total transport. The model is closed by a solid northern wall at 36°N and is forced by steady winds. In the results presented here, large rings separate from the Loop Current in the Gulf of Mexico at periods near 30 weeks. The separation of a single typical ring is shown in detail. The most striking feature is that the separation is not a single spectacular event but a long, gradual process involving recirculation between the ring and the main flow for many weeks after the time at which one would, on the basis of standard observational evidence, normally believe the ring to be completely separated. There is no clear point during the separation sequence at which one can point to the horizontal velocity pattern and say "the ring has just separated."

This is the first modeling study focusing on the Gulf of Mexico that resolves the vertical structure of the currents with more than two degrees of freedom and the first that includes the sills at the Yucatan and Florida straits in a realistic way. The model velocities are lower than those observed in the ocean, but the fundamental idea of the ring-shedding process seems realistic. These results suggest an unexpected complexity in the circulation patterns. The flow in the deeper levels of the model consists of a rich field of vortexlike and wavelike features that travel in company with the upper anticyclone. They travel to the west at a greater speed than the upper anticyclone, and they have substantial north-south motions. They fill the deep basin and interact with the bottom topography. The ring behavior is completely consistent with the observations of Lewis and Kirwan; the deep flow is in keeping with the analysis of Hamilton.

1. Introduction

When we try to understand a complex physical process, it is often helpful to form a simple model. A conceptual model of the separation of Gulf Stream rings during the late 1960s came to be known as "Fuglister's Rope." Figure 1 (from Richardson 1980) shows the basic idea. There was a widely held belief that the process of ring separation was an abrupt and energetic, perhaps even a spectacular, event (e.g., Csanady 1979; Fofonoff 1983); this separation process has been called the oceanographic equivalent of the "big bang." This ropelike model has remained influential because it is a good representation of some parts of what is observed. Figure 2 shows a sequence of satellite infrared (IR) diagrams in which the separation of a warm-core ring appears remarkably similar to the ropelike model. Figure 3 shows similar diagrams from the Gulf of Mexico. In the upper part of Fig. 3, a ring has nearly completed the "necking-down" process that is so essential to ring formation (e.g., Pratt and Stern 1986), and in the lower part, we infer that the ring is almost completely detached and is drifting away. In Fig. 4, however, the ring does not pinch off quite as we might expect; in the top

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panel the necking-down process seems nearly finished, but the middle panel shows that after three weeks have elapsed the ring is still attached. In the bottom panel of Fig. 4 the pattern is similar to the one in Fig. 2, just before the ring separates.

We are naturally curious about how a ring that appears not yet separated can be transformed into a detached ring only a short time later. Most numerical modelers do not rely on the ropelike model for intuition or guidance; when we discuss observations, however, the underlying perceptions often seem strongly influenced by the ropelike idea.

This paper, therefore, has two major purposes. The first is to make a detailed presentation of maps of our model’s velocity field during the time of ring formation and separation. It should be clear that our model does not duplicate the ocean to high accuracy in all details; we urge the reader to remain aware of such limitations. However, the results of this model, as represented by the horizontal flow field, are so different from a ropelike model as to deserve emphasis. These results form the basis for a different conceptual view, and we have found them helpful in guiding our intuition.

The second major purpose of this paper is to present a sequence of maps showing the deep circulation patterns associated with seemingly “isolated” upper-layer warm-core rings. Many studies have suggested that upper-layer warm core rings do not travel in isolation. Because of the enormous observational problems, we do not have clear pictures of the details of deep velocity patterns associated with upper-layer ring studies in the ocean. We find in our model a characteristic family of deep motions that is associated with each large warm-core ring. The topographic waves that constitute the deep velocity field are, in a sense, well known and have been well described by others to the degree possible from limited current meter moorings. Yet the maps of horizontal velocity produced with the model show detail richer by orders of magnitude than earlier descriptions, and these offer exciting possibilities for guiding
For the present purposes we do not consider this a crucial issue. The deep velocities associated with the “upper-layer” rings are known to be an important part of the flow associated with rings. Because this flow is so much more difficult to observe than, for example, the upper-layer flow inferred from IR maps, these initial results may provide insights into the processes by which rings separate. Because the model has not yet been made as realistic as is possible, we do not wish to make extensive comparisons between model results and observations. Nevertheless, we make a few comparisons to show that in many ways these results are consistent with observations. In a later section we compare observed and model velocities.

We made the initial assumption that the fundamental processes that govern the way a ring separates from

Fig. 2. A sequence of paths of the Gulf Stream from NOAA maps of satellite IR imagery. Many details have been omitted in order to emphasize the transition from a large meander to an anticyclonic ring. Time intervals are not uniform.

Fig. 3. As in Fig. 2 but of the Loop Current in the Gulf of Mexico.
the main flow are only weakly dependent on the local flow parameters. Thus, learning about the separation of an anticyclonic ring from the Gulf Stream should be instructive about separations from the Kuroshio or in the Gulf of Mexico. However, the mechanism by which the Spall and Robinson (1990) warm-core ring separates from their model's Gulf Stream seems different from the way rings separate here. Although the flow field in the Gulf of Mexico is similar to that farther downstream, there are important differences. The direction of the flows into and out of the Gulf of Mexico are constrained by topography (as will be seen in later figures). Auer (1987) has shown that the diameters of warm-core rings in the Gulf of Mexico tend to be larger than those of warm-core rings in the Gulf Stream past Cape Hatteras. The 200–400-km rings are similar, and the life spans are similar, but Auer found no warm-core rings in the Gulf of Mexico with initial diameters under 150 km, although small rings have been reported (J. Hawkins, personal communication 1990). Auer reported (his Table 4) that the normalized surface diameter decay rates were identical in the comparison of warm-core rings from the Gulf Stream and from the Loop Current. Brown et al. (1986) studied the characteristics of warm-core rings over a 10-year database. They found that Gulf Stream warm-core rings travel faster (≈6.5 cm s⁻¹) than those in the Gulf of Mexico. Cornillon et al. (1989), however, have shown that the difference is attributable to advection by the larger-scale flow. Kraus et al. (1990) have shown that there is a general tendency for eddy scales to decrease toward higher latitudes, in keeping with the tendency for the internal radius of deformation to decrease. We cannot say whether the constraints on inflow and outflow direction are relevant to the existence of larger rings in the Gulf of Mexico. The large diameter is fortunate, however, for modeling. The grid spacing in the runs discussed below is 1/4°, which clearly gives better resolution in a 300-km ring than in a 150-km one.

The numerical model used here was designed to simulate the western North Atlantic Ocean, the Caribbean Sea, and the Gulf of Mexico: the Gulf Stream formation region. Our results here concentrate on the separation of large anticyclonic rings in the Gulf of Mexico. We refer the reader to the impressive regime diagram of Hurlburt and Thompson (1982), which serves as an example for numerical work, particularly as it relates to models of the Gulf of Mexico.

The effect of rings in the ocean is important, and the literature is extensive; our mention here of relevant work is not exhaustive. Analytical studies of instability mechanisms (e.g., Killworth et al. 1984; Pratt and Stern 1986) are suggestive and are presumably applicable to

FIG. 4. As in Fig. 3 but of the Loop Current in the Gulf of Mexico. The middle panel shows a necking-down process that has persisted for at least 3 weeks. In the bottom panel the ring appears well formed but has still not pulled away from the main body of the Loop Current.
the flow here in the Loop Current. Observational studies on this topic have been discussed by Chassignet et al. (1990), Cooper et al. (1990), Elliott (1982), Maul (1977), Molinari et al. (1977), Morrison and Nowlin (1977), Vukovich and Crissman (1986), Vukovich and Waddell (1991), and others. The observations of ring separation reported by Lewis and Kirwan (1987) are perhaps the most relevant, and their results are consistent with our model results. The work of Hamilton (1990) is the most comprehensive analysis of deep velocity observations in the Gulf of Mexico of which we are aware, and it, too, is consistent with our findings. Numerical modeling results in the Gulf of Mexico have been reported by Hurlburt and Thompson (1980, 1982) and others. The process of ring separation has been studied, for example, by Ikeda and Apel (1981) and by Pratt and Stern (1986). The excellent review of warm-core rings by Joyce (1991), which appeared after this manuscript was first prepared, provides a splendid summary.

The paper is organized as follows. Section 2 describes the model implementation we have used. Section 3 discusses the details of a ring-separation cycle. Section 4 describes the deep flow associated with a ring, and section 5 makes comparisons between the model and observations. The Discussion, section 6, also shows model variability in the Straits of Florida associated with the ring separation cycle. Conclusions appear in section 7.

2. Model description

The numerical model on which these results are based is described in detail in a separate paper (Evans et al. 1992). It is the so-called Bryan–Cox–Semtner–GFDL primitive equation model, implemented here at 1/4° horizontal resolution (Cox 1985; Semtner 1986). For the results shown here, the model is forced by steady winds. Forcing by time-dependent winds, although a logical next step, is not employed here. An important feature of this model implementation is that it has no open boundaries. The Gulf Stream flow is limited by a northern wall at 36°N and an eastern boundary along 49°W near the mid-Atlantic Ridge (see Fig. 5). A forcing mechanism at the eastern boundary patterned after earlier work by Holland (sometimes called "pumps and baffles") supplies a proper temperature and salinity in the "inflow" from the virtual ocean as well as the appropriate vertical shear; this boundary region is 6° wide. We use the vertical geostrophic shear from historical hydrographic data (Levitus 1982). The total barotropic flow at the eastern boundary is set from the integrated wind-stress curl between the African coast and the model's boundary. At the northeastern edge of the model, nothing special is done to force the inflow from the Gulf Stream back into the pumps and baffles region. Although inclusion of such forcing might have been necessary, the flow in the Gulf Stream moved into the pumps and baffles region with no artificial encouragement.

The model was spun up at coarse resolution (1°) for 4 years. An intermediate spinup run of 7 years was done at 1/4° resolution in which minor adjustments were made to the model. A longer run at that point was begun in which no changes were made. The times shown in the figures or in the text will describe times beginning with this last series.

Figure 5 shows the full domain of the model. A large anticyclonic ring in the Gulf of Mexico has begun the separation cycle but is still attached to the primary flow in the Loop Current (upper panel). In the lower panel, the streamfunction map suggests that the ring has separated. The transport through the Straits of Florida—approximately $19 \times 10^6$ m$^3$ s$^{-1}$—is considerably less than observed. One reason for the lower transport may be that we have not used sufficiently energetic winds. Recent work (Boning, personal communication) suggests that the use of mean winds, such as those of Hellerman and Rosenstein (1983), does not force sufficient flow through the Straits of Florida. Alternatively, it may be that our eastern boundary conditions (i.e., the pumps and baffles region) are not vigorous enough in creating the total mass transport. In the continuing development of this model we have improved the structure of the forcing in the eastern boundary to force more realistic flow, and have added an additional component that is consistent with recent ideas of low-latitude cross-equatorial flow (Schmitz and Richardson 1990). These changes have made the model velocities consistent with observations but do not appear to have changed the substance of the results presented here.

For these reasons, one of the shortcomings of the results shown here is that the velocities are too low. A typical peak velocity in the model is $\sim 145$ cm s$^{-1}$, or less than 3 kt in the upper level in the high-velocity region just to the east of the Yucatan Peninsula, and $\sim 100$ cm s$^{-1}$ in the free flow in the Loop Current to the north. Observed velocities, however, are sometimes found to be as much as 50% greater. The flow fields shown here as representative of the upper layers are in the third level (80–180 m), where the velocity is less than that at the sea surface. Lewis and Kirwan (1987) reported no ring-swirl velocities larger than $\sim 85$ cm s$^{-1}$, and found that they were rarely above 75 cm s$^{-1}$. The swirl velocities in our results tend to be below 70 cm s$^{-1}$, so our model velocities are too low.

A vertical cross section of the instantaneous model velocity in the Yucatan Channel (not shown here) resembles, except for the magnitudes, any one of the observed sections in the Florida Current (e.g., Schott et al. 1988) or that in the Straits of Yucatan (Maul et al. 1985). The maximum speeds are concentrated toward the western side, the speeds decay to small values near the bottom, and there is often deep flow to the south. There is also weak southerly flow in the eastern part of the section. Comparison with observations is saved.
for a later section; because the model is not yet fully developed; however, it is not appropriate to make such comparisons in great detail. The focus of this paper is the process of ring separation.

In the runs with steady forcing, the rings separated from the Loop Current at a periodicity of approximately 30 weeks. Sturges (1992) has found in the spectrum of Loop Current variability a primary peak near 8.5 months (37 weeks), which is attributed to the basic ring-shedding cycle. The rate at which rings are shed is one of the fundamental observables of the system; we are encouraged that there is fair agreement between the ring-shedding cycle in the model and in the ocean, with no arbitrary tuning to accomplish it. This point brings out another difference between the ring-separation cycle here as opposed to the equivalent behavior in the Gulf Stream: Spall and Robinson (1990) show how the whole process is completed within ~30 days rather than ~30 weeks.

The depths of the 12 model levels are shown in Fig. 6 and Table 1. In regions of extremely steep topography, a limited amount of smoothing was done to improve numerical stability. It is likely that the small-scale numerical noise observed in the model near the Campeche Escarpment could be improved with better vertical resolution (see, for example, Weaver and Sarachik 1990). Some interpolations occur in the transition from the actual topography to the 1/4° grid; all the Caribbean islands do not appear in Fig. 5, because in the smoothed topography they exist only up to level 1.
The depths shown in Table 1 were selected on the basis of both the density stratification and the major topographic features. Note that the maximum depth in the model runs presented here is the maximum depth in the Gulf of Mexico. We have also made a preliminary series of runs with a 15-level model. This version of the model represents the bottom beta effect on deep motions more accurately. It does not appear to have a significant effect on the ring-separation cycle, however, and is not discussed further here.

We have chosen to use constant horizontal eddy viscosity (5 × 10^6 cgs units for mixing of momentum, 3 × 10^6 for temperature, and 1 for vertical mixing of momentum). Semtner and Chervin (1988) found that the use of higher-order eddy viscosity allowed the generation of Loop Current rings with coarser grid spacing. By contrast, Hurlburt and Thompson (personal communication) are using grid resolution that is finer by a factor of 3 than we have used here. They (and others) find that increased resolution improves many features of the model performance. Our decision was to use the simplest form of eddy viscosity so as not to add physical uncertainty. This implementation uses no explicit bottom friction.

**Runs with reduced horizontal viscosity**

We made a series of exploratory runs with horizontal eddy viscosity reduced by 40%. In these studies, the peak velocity at the surface in the Loop Current region increased, and velocity and total transport in the ring increased, but small-scale noise also increased. At this stage of model development, we were more concerned with obtaining physical insight than with trying to duplicate any specific features of the flow. Therefore, we have done nothing artificial to try to increase the surface velocities.

The position at which the rings separate in the model (as shown later), while slightly farther to the northwest than is typically observed, is still well within the observed range. In the series of model runs with reduced horizontal viscosity, the position at which a ring separated appeared to be more in keeping with typical observations. The period at which rings separated became more variable, but with the limited set of runs it was not possible to learn whether the mean value changed.

### 3. A ring-separation cycle

Figure 7 shows a map of horizontal velocities at level 3 in a limited region of the model. (The bottom of level 3 is at the edge of the continental shelf.) What will become the Florida Current flows into the Gulf of Mexico and out again between Cuba and the southern tip of Florida. Just north of the Yucatan Peninsula a large anticyclonic ring has formed but is still attached to the main flow.

Three features seem important here. First, part of the inflow in the Yucatan Channel continues to flow to the north and northwest around the still-attached anticyclonic ring. Much of the flow out of the Gulf of Mexico is involved in the flow along the eastern edge of the nascent ring. Second, although the ring has not yet separated from the Loop Current, there is recirculation in the interior of the anticyclone.

Third, we see that recirculation is already taking place in the southern part of the Loop Current between the Yucatan Peninsula and Cuba, at a latitude of ~23°N while the anticyclone to the north is still attached. These features are consistent with inferences from hydrographic data. Nowlin (1972) shows that the dynamic height inside the Loop Current (see his Fig. 1-29, p. 37) is significantly greater than one would ex-

### Table 1. Model depths (meters).

<table>
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<th>Level</th>
<th>Box height</th>
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<th>Depth (bottom)</th>
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<tr>
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<td>900</td>
<td>3170</td>
<td>3620</td>
</tr>
</tbody>
</table>
pect based on the external flow field alone; see also Molinari (1977). Even more important, direct observations of the surface flow by drifters as reported by Lewis and Kirwan (1987) support each of these three aspects of the results. Their discussion of the separation cycle (see p. 11736) anticipates (and supports) the model results presented here.

The velocities in the Loop Current at level 3 in Fig. 7 reach only \( \sim 60 \text{ cm s}^{-1} \). As mentioned earlier, realistic maxima in the observed flow are larger. We expect that some of the details of these features will change with more realistic winds and with stronger boundary forcing. Although the peak speeds in the model are not realistic, we are unaware of any reason to suspect that the major features of the flow will change in any fundamental way as a result of higher velocities.

In the lower right-hand part of Fig. 7 the outflow from the Caribbean approaching the Yucatan Straits is surprisingly concentrated in a westward flow. Comparing this with Fig. 5, however, we see that this flow is not constrained by a model boundary but is well within the interior of the model; the flow is consistent with the topography of the Nicaraguan Rise.

We have somewhat arbitrarily chosen Fig. 7 as the starting point for our description of a ring-shedding cycle. Figure 8 shows the long gradual process by which the ring travels to the west until it combines with the anticyclonic gyre already present in the western Gulf. At week 366 the map of mass transport streamfunction for the whole water column (Fig. 5) suggests that the ring has separated. The velocity distribution in Fig. 8, however, still shows that at week 366 a great deal of the northward flow in the Straits of Yucatan first goes around the anticyclone, then around the eastward cell of the Loop Current, and on out of the Straits of Florida. Many weeks later (depending on the size of the figures and the reader's visual acuity), after the streamfunction maps would have suggested the separation of the ring, many of the velocity vectors in Fig. 8 show that the flow on the western side of the Loop Current remains connected with the southern portion of the anticyclone now in the center of the Gulf of Mexico.

By week 380, the connections involving eastward flow between the anticyclone and the Loop Current are difficult to discern in Fig. 8. We have also examined maps of temperature in the upper levels (not shown). By week 376, a time when one would infer
from Fig. 8 that the ring has separated, there are closed
temperature contours, showing that the ring is indeed
transporting fluid.

The center of the anticyclonic gyre by week 380 is
at approximately 93°W. South of the ring’s center, be-
tween it and the Mexican coast, the flow is all to the
west. At this point it is difficult to see any distinction
between the new anticyclone reaching the western Gulf
and the large anticyclonic flow field originally present.
Figure 8 shows that by week 388 or 390 the cycle is
starting over. A number of details show that the cycle
does not repeat exactly, but the gross features of the
separation cycle are similar. We should emphasize that
our choice of horizontal eddy viscosity in these runs is
slightly high, a choice that will accentuate the inter-
connecting velocity fields between the detached ring
and the main flow. We also point out, however, that
the induced interconnecting flow is consistent with
ideas of turbulent entrainment and vorticity dynamics.

The most striking feature of this sequence of patterns
has to do with the precise point of separation. It is clear
at the beginning of this sequence that the ring has not
yet separated, yet it is difficult to point to any specific
time at which one can state that the ring has “just sepa-
rated.” It is true, of course, that other properties are
relevant to the question of ring separation. One asks
whether fluid is transported within the ring (see Nof
1983; Flierl 1984). The contours of potential vorticity
are instructive of course; see Davey and Killworth
Such calculations are important and are straightforward with the model output—if much more difficult with realistic data. At this stage in the development of our model, however, it seems important to concentrate on qualitative features. We wish to emphasize here primarily the distinction between ring separation as a “catastrophic event” and the gradual process depicted in Fig. 8.

Figure 9 shows the path of the centers of the anticyclones. The ring translation speed, 5 cm s⁻¹, matches the observed speeds quite well. The path is similar to one shown by Vukovich and Waddell (1991, Fig. 1), except that their data show a more abrupt transition from westward to northward. Vukovich and Crissman (1986) find similar speeds for ring translation although with large variability; most observations of ring in the Gulf show erratic trajectories as well. Cornillon et al. (1989) went to considerable effort to remove the effect of larger-scale advection from the observed speed of Gulf Stream warm-core rings and found essentially the same mean speed as we have here. Chassignet et al. (1990) concluded that there is a clear tendency for rings in models and in the ocean to travel faster than expected, even when advection is taken into account.

In a numerical model the rate at which the horizontal velocity decays away to the side of a strong flow is determined in part by horizontal eddy viscosity, although in this model nonlinear advection is also important. It is difficult to see how the fundamental concept of ring separation shown here could be significantly altered by reasonable changes in the model’s eddy viscosity. The amount of small-scale turbulence, however,
is strongly conditioned by horizontal eddy viscosity. The solutions might change considerably if such turbulence were present.

4. The deep velocity field

The flow in the surface layer of the Loop Current continues out through the Straits of Florida at depths approaching 800 m (e.g., Richardson et al. 1969). The flow in the Loop Current and in the large anticyclonic rings is highly coherent throughout the upper part of the water column. Figure 10 shows the flow in the model at three representative deeper levels. The position of the upper ring center is shown by the dot. Level 7 is the first of the deep levels in which the flow does not continue out through the Straits of Florida past Miami. The flow in this level, however, is often similar to that of the upper part of the water column as represented by level 3.

Level 9 represents a level in which the deep flow is continuous between the Gulf of Mexico and the Caribbean Sea. Level 11 represents the deepest level. The major differences in the appearance of these levels in this figure arise from the differences in scaling of the vectors, which is based upon the maximum velocities; the large apparent difference between levels 7 and 9 is an artifact of this scaling. In these levels, a family of deep vortex-like motions stands out. These features are not isolated, nonlinear vortices of the type found in the upper ocean. Because the velocities are weak (only ~5 cm s$^{-1}$), these features are topographic Rossby waves, as described by Hamilton (1990). The flow near the Yucatan Channel shown here and in subsequent figures is remarkably similar to flow at the sill reported by Maul et al. (1985).

Beneath the upper anticyclone, but offset to the northwest (at this time of the cycle), Fig. 10 shows, in all 3 levels, a deep anticyclonic feature. To the east of it we see a long peanut-shaped, nearly double cyclonic vortex. It, too, appears similar at all levels. Although there are differences in detail, one gets the impression when looking at many figures of this type that the deep flow is vertically coherent throughout all levels in the deep water.
Figure 11 shows a series of maps, analogous to those in Fig. 8, using level 9 to represent the flow in the deeper part of the model. One can follow the motion of the deep velocity field in Fig. 11 and trace the motion of each individual high and low feature. The two primary vortexlike features in the center of the pattern are quite distorted, however, as they move to the west.

A remarkable change in the deep flow field takes place during weeks 370 through 376 (see Fig. 11). As the primary cyclonic feature in the east propagates to the west, it interacts with the southern boundary, and travels between the anticyclone and the boundary. We see that by weeks 386–390 the pattern of flow in the western Gulf is remarkably similar to the set of highs and lows that had been there at week 362. Nevertheless, the progression of events shown in Fig. 11 tells us that each feature has been replaced by a new member of the family. Thus, we can be certain that the highs and lows of the deep flow move about relative to the upper ring. The cyclonic feature that was originally northeast of the upper anticyclone is south of it by week 384. Hamilton (1990) showed that the deep currents observed at a few moorings could be understood as topographic Rossby waves. Here the available detail in the model allows us a comprehensive view of the flow and can help in guiding our intuition.

5. Comparisons between measured and modeled simulated currents

a. Currents measured at moorings

To compare model results with observed currents, many locations were selected within the model and time series of velocity data were archived by sampling every 2 days at every model level. For a number of reasons, as discussed earlier, the motions of the Loop Current in the model are too slow and too regular. There is no interaction between the Loop Current and the edge of the shelf. Without these interactions, two classes of motions are not produced: topographic Rossby waves in the 30-day band, as described by Hamilton (1990), and eddy interactions near the shelf edge. This does not indicate that the model is "wrong," simply that these motions are not forced. Spall and Robinson (1990) reported that even with time-dependent forcing their model did not produce these motions in the flat-bottom version, but required the inclusion of realistic bottom topography.

b. Currents near mooring G

Figure 12 shows the locations of several current-meter moorings from the Minerals Management Services (MMS) program in the Gulf of Mexico (SAIC 1987). Figure 13 shows model velocities extracted from levels 1, 3, 5, 9, and 11 at a location near mooring G. The most complete records obtained from mooring G are at the deeper levels, 1565–3174 m, which correspond to model levels 10–12. Hamilton (1990) showed (his Fig. 3) that the observed currents were uniform at the deeper levels. We find the same result in the model; in Fig. 13 the currents at level 11 can hardly be distinguished from those in level 9.

The peak surface speeds in the model near "G" are slightly above 60 cm s⁻¹; the actual observations (at ~400 m) are similar, although the frequency distributions are quite different.

At depths of 1500–3000 m, observed velocities reach ~20–25 cm s⁻¹. The model values reach peaks near 12–15 cm s⁻¹, which is obviously much less.

What is far simpler to observe in the model, however, is the topographic Rossby wave (TRW) behavior in the deeper part of the basin. Hamilton was able to decipher these motions by skillful analysis. By examining the output from the model, it is immediately obvious that a set of coherent deep motions is propagating from east to west. These TRWs behave essentially as deduced by Hamilton. He noticed that the deep TRWs propagated somewhat faster to the west than the upper anticyclone. This feature is seen in the figures here as well. The fact that the deep velocities in the model are less than those observed will not significantly affect linear wave behavior.

c. Near mooring GG

Figure 12 shows the position of mooring GG near 92°W, in 3000-m depth. Hamilton (1990) has analyzed the currents there, and shows (his Fig. 7) that the currents are similar at the 1650- and 2500-m instruments. Figure 14 shows the observed currents at 305 m and at 1650 m at mooring GG. The largest speeds at the deeper instrument (approaching ~20 cm s⁻¹) are associated with the passage of rings. The remarkable feature is that the large speeds at 305 m occur at a time when weak speeds are observed at the lower instrument. Figure 15 shows model currents as the deep motions go past simulated current meters; level 9 has a central depth at 1470 m and seems appropriate for comparison. The observed currents have peak speeds of ~20 cm s⁻¹. Those in the model are much weaker, reaching approximately 25 cm s⁻¹ in the upper levels and less than 6 cm s⁻¹ at level 9.

There is substantial vertical shear between the near-surface (level 1) flow and that in levels 3, 5, and 9. There is very little shear below level 9, however, and in this respect, the model is in accord with the observations. As was discussed earlier, we attribute the low speeds in the model to the fact that the (forced) inflow at Yucatan is not strong enough.

d. Near mooring P

Figure 16 shows the observed currents at mooring P. For comparison, Fig. 17 shows currents extracted
from the model at a location very near P. We see that speeds of $\sim 10$ cm s$^{-1}$ are observed as deep as 1500 m. By contrast, the model velocities are, at best, approximately half that value. This remains consistent with the smaller values found in the model at GG. To get a more comprehensive understanding of the flow field, however, the figures in section 4 offer full horizontal maps from which these plots are a subsample.

c. Currents measured along ADCP sections

The best near-surface velocity cross sections are obtained with a ship-mounted Acoustic Doppler Current Profiler (ADCP). In one such experiment (SAIC 1987) the near-surface velocities occasionally reach $\sim 225$ cm s$^{-1}$, but peaks are typically 170–190 cm s$^{-1}$. The 150 cm s$^{-1}$ contour rarely extends below 100 m. Lewis and Kirwan (1987) found peak swirl speeds of $\sim 80$ cm s$^{-1}$, shortly after a ring separation, from a buoy drogue at 200 m.

Cooper et al. (1990) observed similar speeds in rings, with near-surface peaks of $\sim 200$ cm s$^{-1}$. There is such strong vertical shear, however, that by 200 m the speeds are dramatically reduced. Their Figs. 18 and 19 show speeds at 200 m that are reduced to only 30%–40% of the surface values.

Thus, we find that the observed, peak surface velocities are significantly larger than those produced by the model. By depths of 200 m, however, the disparity is greatly reduced. Peak model speeds of $\sim 60$ cm s$^{-1}$ at
level 3 are still less than we would prefer, but are not wildly unrealistic.

6. Discussion

Some generalizations can be drawn from these results. If we think of the sequence in Fig. 8 as representative of one ring-separation cycle, we can examine the central times, weeks 374 or 376, as the out-of-phase center part of the cycle. It is clear that in many areas of the basin the flow reverses, so that the net flow would be expected to be small. In some parts of the basin, however, the flow does not reverse. For example, along the western boundary from approximately 21°N to approximately 25°N the deep flow is always southward.

No one should expect an exact correspondence between the model and the ocean in the details of the flow field. Nevertheless, it seems instructive that there are regions in the model in which the flow does not reverse; these regions can be explored for first-order mean flows.

In the upper levels of the flow, Fig. 7 shows that at the beginning of the cycle, the flow at the western boundary is to the north, but farther offshore (approximately 94° to 95°W) the flow is to the south. This flow farther offshore is reversed by week 378 as the anticyclonic ring goes by, suggesting weak mean flow. At the western boundary, however, the flow appears to be uniformly to the north at all times. Such flow was also found by Hurlburt and Thompson (1982). Figure 18 shows the model flow in the "western
boundary current” at 26°N, 96°W, somewhat inshore of mooring P. The northward velocity component in the model reaches approximately 45 cm s⁻¹ near the surface. The northward velocity extends to the bottom here. The speeds in Fig. 18 are strongly modulated by the addition of each new ring. The flow here is strong because of a western boundary current that results from the combined effects of rings and of the large-scale wind-curl forcing (Elliott 1982; Sturges and Blaha 1976). A wind-driven western boundary current develops in the model even before rings form, as is well known. We do not yet understand the relative importance of wind-curl forcing and of ring forcing. A series of experiments is planned to shed light on this question.

Figure 11 suggests that the anticyclonic flow at the northwest corner does not reverse in level 9. Observations, however, show that cyclonic features are often found in the northwestern Gulf, driven by mechanisms not yet implemented in the forcing of our model.

The physical mechanisms by which the new ring merges with the old ring already present in the western Gulf are clearly not realistic in the model. It is known that the merging process is often accompanied by the presence of filaments extending beyond the edges of each ring (for example, see Cushman-Roisin 1989; Nof 1988). The horizontal resolution of the model (1/4°) is inadequate by at least an order of magnitude to allow such features to be realistically included.
flow in the Straits of Florida in greater detail. At the three locations shown as F1, F2, and F3 in Fig. 12, the velocity fluctuates over each ring cycle; the amplitude of the fluctuations decreases with depth. The peak velocity (≈60 cm s⁻¹) in the model is found at the northern position. The fluctuations in velocity, averaged at these three locations, are shown in Fig. 19.

The most remarkable feature is that the fluctuations are so small! The peak-to-peak changes associated with the ring-separation cycle are only ≈5 cm s⁻¹. The fluctuations observed by Schott et al. (1988), by contrast, are ≈150 cm s⁻¹. The important point is that the variability reported by Schott et al. is associated with the natural variability of the flow in the Florida Current and has essentially nothing to do with a ring-shedding cycle. What we learn here is that variations in the model velocity field associated with ring separation are surprisingly small.

After this part of the work was completed, additional model runs were made in which the boundary forcing was modified significantly. At the extreme southeast corner of the model, we added an additional 14 Sv of near-surface inflow, in keeping with the recent results of Schmitz and Richardson (1991). This flow is not

A remarkable feature (seen in Fig. 11) is that the upper-ring center lies just above what could be called a weak deep jet. The deep velocities here are only ≈3 cm s⁻¹, but this is not small in comparison with the westward translation of a ring: the westward motion of the upper ring could be enhanced by the deep flow.

From the runs at 1/4° resolution we performed a spectral analysis of the transport between Florida and Cuba. The ring cycle fluctuates with intervals of ≈27–64 weeks, but the only feature in the spectrum is a peak near 30 weeks. By examining the weekly streamfunction maps, we found that the times of ring separation coincided with the times of maximum transport between Florida and Cuba. We have made a point of showing that a ring does not become separated from the Loop Current in a single event; nevertheless, there is a stage at which the westward motion of the ring begins to be significantly different from the motion of the Loop Current, as shown in Fig. 9. An observer examining the figures from the model output can, with little ambiguity, identify the time at which the ring begins the separation process, as evidenced by its westward translation.

To explore the relation between transport fluctuations and ring separation, we have examined the model

Fig. 15. Model currents from the location of mooring GG (see Fig. 12). The E–W component is above; the N–S component is below. These are shown for levels 1, 3, 5, 9, and 11. The time axis, based on the final 7 years of model runs, coincides with the earlier figures of velocity plots during the ring separation.

Fig. 16. Observed currents at mooring P in the western Gulf. Data are shown for two depths; these data have been low-pass filtered to suppress all fluctuations having periods shorter than 8 days. The filtered data start on 19 June 1985; 311 daily values. These is no correspondence between these data (calendar) times and model time, except for frequency.
Fig. 17. Model currents from a location a few kilometers to the east of mooring P (see Fig. 12). The E–W component is above; the N–S component is below. These are shown for levels 1, 3, 5, 9, and 11. The time axis, based on the final 7 years of model runs, coincides with the earlier figures of velocity plots during the ring-separation cycle.

Fig. 18. Model currents from a location near the western boundary of the Gulf, at 26°N, 96°W, 90 km to the west of mooring P (Fig. 12). The E–W component is above; N–S is below. These are shown for levels 1, 3, 5, and 8, as the model extends only to that level (1120 m) here. The time axis, based on the final 7 years of model runs, coincides with the earlier figures during the ring-separation cycle.

wind-curl driven at these latitudes, but comes up from the south. After this additional forcing was added, the transport in the Florida Current system increased substantially, to values much more consistent with observations, and the velocities in the model increased. This work is being reported separately.

7. Conclusions

Through the use of a 12-level primitive equation model of the western Atlantic, Caribbean Sea, and Gulf of Mexico, we have studied the separation of large anticyclonic rings from the Loop Current. We describe in detail one typical cycle. A most striking aspect of the flow is that at no single time was it possible to say unambiguously that the ring “has just separated” from the Loop Current. That is, the process of separation is not clear or sudden. By contrast, in our model the ring grows, propagates away, and separates only as a gradual process.

The ring-separation process in our model is consistent with the observations of Lewis and Kirwan (1987). The speed of western propagation is correct, and the rate at which rings shed is approximately correct. The main shortcoming of the model is that the transport is too small and the velocities too slow. This has been improved by making the boundary forcing more nearly realistic; that was not our primary concern, however, in the initial development of the model.

The flow beneath the upper anticyclonic ring consists of a rich field of vortexlike features of both signs that

Fig. 19. Variation in velocity in the model at positions F1, F2, F3 averaged. Levels 1 (solid) and 3 (dashed) are shown. The time axis, based on the final 7 years of model runs, coincides with the earlier figures during the ring-separation cycle.
propagate as topographic waves. The wave field is linear in the deeper levels, as the peak velocities are only ~5 cm s⁻¹. It is usual to see roughly half a dozen such high and low features in the deeper levels of the model. They fill the basin completely and are clearly influenced by the bottom topography. The deep vortexlike patterns change position relative to the upper ring. They propagate to the west at speeds somewhat greater than that of the upper ring. These results are consistent with those of Hamilton (1990).

Some regions of the flow show reversals from strong northward flow to strong southward flow while other regions, typically those along the western boundary, show consistent flow in one direction throughout a ring cycle. For the cycle we have shown here, there is flow uniformly to the north along the western wall, north of approximately 24°; this anticyclonic flow extends to the bottom. In the deeper levels of the model in this realization there is consistent southerly flow south of approximately 24°N along the western margin.

There are points in the ring-separation cycle at which it appears that the ring has separated, as evidenced by a translation speed to the west; these times of separation coincide with times of maximum model transport in the Straits of Florida. The velocity fluctuations, however, are only ~5 cm s⁻¹ in the straits, and so are much smaller than natural fluctuations from other causes such as the annual cycle of transport.

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