

CHAPTER 1: AN INITIAL SURVEY

SECTION 2

Organizational Notes for Chapter 1 are contained in this paragraph: This is the second section of Chapter 1, called Chapter 1.2. Chapter 1 is organized into three parts or sections, in order to limit the time required to download and print any section, especially its figures. There are occasional underlined sub-section headings. Part 2 of Chapter 1 (Chapter 1.2) is a preliminary consideration of processes and mechanisms and numerical model results for the GOM, mostly for the eastern Gulf, but also including a brief view of some of the processes in the western Gulf. Section 1 of Chapter 1 (Chapter 1.1) contained a preamble that considered mostly general background information, including some historical material, and then moved into an introductory survey of the Loop Current and its Eddy Field (collectively called the Loop Current System in this review), primarily in the eastern Gulf. Section 3 (Chapter 1.3) involves an initial look at coastal circulations and their interactions with the flow patterns in deeper water in the northwestern Gulf, in partial preparation for Chapter 3 and Volume II. Chapter 1.3 also contains a Brief Summary of Chapter 1, ending with an outline of the composite Review (with the focus on Volume I). Chapter 1.2 was last updated on 21 November 2003, and there are about 11 pages and five illustrations involved (Figures 1-15 through 1-19). Page and figure numbering is by Chapters, not Chapter Sections. Figures follow the corresponding text sections.

The introductory survey of the Loop Current (LC) and its Eddy Field that was started in Chapter 1.1 is extended in Chapter 1.2 to include a preliminary discussion of mechanisms and dynamical considerations, emphasizing numerical model results, especially their intercomparison with observation. The processes and mechanisms associated with the formation of Loop Current Eddies or Rings (a maturely separated LCR, and associated port-to-port LC were shown in figures 1-5 and 1-12, and many other examples are shown in Chapter 2, as well as throughout this review) have been the subject of numerous previous investigations. Many references related to the process of eddy separation from the LC are cited in the present chapter section, and Chapter 4.3 contains a summary of these issues. Several distinguishable processes or mechanisms are involved in the full or composite LCE formation and separation sequence, which may involve deep as well as upper layer (depth 800-1000 m or less, nominal) flow characteristics. The initial step in the composite separation sequence involves extended northerly or northwesterly movements by the LC into the Gulf (similar to the red line pattern in figure 1-4), leading to configurations north of the port-to-port pattern (the green line pattern in figure 1-4), and possibly penetrating to the vicinity of the ~200 m depth contour off the Mississippi-Alabama Shelf. LC boundary configurations of the generally extended type were also

shown, for example, by the upper layer isotherm depth distribution in Figure 1-7, as well as by the SST maps shown in figures 1-10 and 1-11. SST maps typically suggest a somewhat more northerly penetration of the LC into the Gulf than is visually obvious in the SSH Maps. The idea that LCR formation involves instability processes was pioneered by Ichiye (1962) and Reid (1972), along with Hurlburt and Thompson (1980, 1982; hereafter HT8082), and several of the follow-on publications to HT8082 are discussed below and throughout this review. The significance of instability processes in the fully-developed mid-latitude Gulf Stream System was initially demonstrated by Holland and Lin (1975a,b), notably as a source of mesoscale eddies that led to eddy-driven recirculations, in qualitative agreement with observation (Schmitz and Holland, 1982; Hogg and Johns, 1995). The first explicit observational studies of the influence of cyclones on the structure of the LC in the context of warm-core eddy separation followed by westward propagation of these anticyclonic current rings was by Cochrane (1969b, 1972). This picture was extended in the context of frontal eddies and deeply penetrating cyclonic features by Vukovich et al. (1979a) and Vukovich and Maul (1985), along with eddy propagation with a westward component (Vukovich and Crissman (1986). Various recent studies of Loop Current penetration by cyclones and separation along with propagation (including along path interactions or modifications) are at the forefront of research in the Gulf today (for example, Fratantoni, 1998; Fratantoni et al., 1998; Hamilton et al., 1990; Zavalla-Hidalgo et al., 2003). A realistic depiction in numerical model results of the cyclones that are observed to broker ring formation requires comparatively small horizontal grid resolution and eddy viscosity, which have just begun to be adequately explored. The investigation of other components of the composite separation process include studies of the upper and lower layer (depths greater than 800-1000 m, nominal) transport characteristics involved with co-oscillations between the Gulf and Caribbean (Maul 1977, 1978; Maul et al., 1985; Oey, 1996; Bunge et al., 2002; Ezer et al., 2002, 2003; Oey et al., 2003) associated with an extension of the Loop Current into the Gulf (ie.. the formation of a loop) in mass balance terms. Recently, investigations of the influence of upstream conditions and forcing in the Caribbean Sea and tropical western North Atlantic on the composite LCE or LCR separation process has seen renewed activity (Oey et al., 2003; please also see Murphy et al., 1999).

The earliest studies using numerical model results in process mode that explicitly demonstrated warm-core ring formation and an idealized version of the mechanism(s) of separation of warm-core eddies in the context of dynamical ideas (instability processes) in the Gulf of Mexico were by HT8082. These papers, which will be constantly referenced throughout this review, concentrated initially on what is known as barotropic instability. In this idealized case, the kinetic energy in the Loop Current is transferred directly to a LCR when it pinches off, a “conversion” of mean kinetic energy to eddy kinetic energy. According to HT8082, their model Loop Current did not necessarily meet any instability criterion during most of the interval between eddy shedding, so that the time interval required for ring formation was not determined by an instability growth rate, but by the time required for the Loop Current to penetrate into the Gulf and bend (the northerly segments of the LC propagate relatively westward) to an unstable

configuration, at which time an instability grows very rapidly. In the early HT8082 numerical experiments, the unstable configuration reached by westward bending was not compatible with the database. The ring shedding period was found to depend on an internal Rossby wave speed, the eddy diameter, and an angle of inflow for the Yucatan Current, with a natural (constant) period of about 10 - 11 months for the parameter choices they made. A Regime Diagram for their simplest model configuration exhibiting barotropic instability is presented in Appendix C (Figure C-1). HT8082 also examined to some extent the relative roles of deep currents and baroclinic instability and topography. More complex and realistic cases, which might also involve both more realistic configurations of the LC and even episodic as opposed to constant ring separation intervals, were pursued further in the mid-1980's, [for example, Hurlburt (1984, 1985, 1986) and Wallcraft (1985,1986)], and most recently in numerical studies by Oey et al. (2003). Wallcraft (1986) was the first numerical modeling study to use 10 km horizontal grid resolution in the Gulf, a significant step that was overlooked until the late 1990's. HT8082 did not consider local wind forcing, or the details of temporally and spatially varying upstream conditions (these topics were briefly examined as discussed below). Their model results were driven almost exclusively by constant inflow boundary conditions (port forcing) that were specified at the Yucatan Straits, and HT8082 examined the results of various transport stipulations there, as did Wallcraft (1985, 1986). Wallcraft (1986) considered both local wind and port forcing. These numerical modeling studies from the 1980's are described in more detail in Chapter 2.4 and Appendix C.

Twenty km horizontal grid spacing (and larger) was used for many numerical experiments throughout the oceans over the past 20 years, but to resolve various eddy field characteristics and mean flow features, 10 km grid spacing tends to yield results that are about twice as realistic as 20 km (Schmitz and Thompson, 1993; please see also Hurlburt and Hogan, 2000). For the GOM at this time, horizontal grid spacing (and eddy viscosity) should be chosen to resolve the frontal eddies that play a role in the LCR separation process, and filaments that interact with coastal circulations, requiring a horizontal grid interval of 3-5 km, or even smaller in the coastal regions. The earliest discussion in terms of processes with a specific type of vertical structure in the Loop Current Regime that I am familiar with was in the numerical modeling paper by Hurlburt and Thompson (1982; their section 8.3), where deep counter rotating vortex pairs were found, called Modons there [involving eddy-like currents at depth (that is, in their lower layer)]. There are surprisingly few deep data relevant to this question presently available from the abyssal Gulf. At this time (mid-2003), only a handful of current-meter moorings were ever deployed in the Gulf until recently (Hamilton 1990, 1992, 1998, 2000), and only a couple of these in the vicinity of the Loop Current Regime. However, Inoue (1998) and Welsh and Inoue (2000) have recently drawn attention to this situation and a pilot field program is underway (Dr. S. E. Welsh, pers. comm.). There are also now notable new results by Sheinbaum et al. (2002), a brief summary of the most recent findings from the first mooring deployment during the CANEK field program, involving direct current measurements from an array set from September 1999 to June 2000 across

the Yucatan Channel. In addition to the moored instrument and other associated results obtained during the first setting of the CANEK array, studies of the time-dependent exchange between the Gulf and Caribbean by Bunge et al. (2002) are of special importance, and there are also new summaries of the characteristics of the statistics of the time-dependent structure of the Yucatan Current (Ochoa et al., 2001; Candela et al., 2002) that contribute to an assessment (Chapter 4.3) of the role of previous observations, and that are relevant to model evaluation (please see, for example, Ezer et al., 2002, 2003). There have been several moored array deployments throughout the Gulf on the continental shelves, slope and rise. In these kinds of regions, Hamilton (1990), Oey (1996), Oey and Hamilton (2002a,b) and Oey and Lee (2002) have suggested that the deep current variability over the slope/rise regime in the northern and western Gulf may be dominated by topographically linked waves radiating from the vicinity of the Loop Current System, perhaps in analogy with the Gulf Stream Regime, please see Chapter 2.4 (near its end), and Appendix C.

It is typical and demonstrably useful, when using numerical experiments to examine processes, to start with idealized model configurations and application choices that are gradually made more realistic while carrying out various sensitivity studies. The earliest studies described in the last few paragraphs, were with comparatively simple two-layer models. Later studies with more complex model formulations have been published by Sturges et al. (1993), Dietrich and Lin (1994), Oey (1996), Welsh (1996), Dietrich et al. (1997), Welsh and Inoue (2000), Oey and Lee (2002), Oey and Hamilton (2002a,b), Ezer et al. (2002, 2003), and Oey et al. (2003). At this time, numerical predictions of the circulation of the Gulf are in an embryonic form (Kantha et al., 1999; Herring et al., 1999). HT8082 found that their lower layer flow in the vicinity of the LC or a LCR was characterized by deep cyclone/anticyclone pairs, and this structure is present in other numerical experiments with different model configurations as well. In very general and qualitative terms, this type of vertical structure, where current directions can change in the vertical dimension by large amounts in the vicinity of 800-1000 m depth, were also a basic characteristic of the model results presented by Sturges et al. (1993), even though their model current amplitudes are too low by at least a factor of 2 (please see Chapter 2.4 and Appendix C for more detail). The upper layer kinetic energies that emerge from the Oey (1996) model results are also rather low. Numerical model results from the 1990's for the general circulation in the GOM tended to generally be weak in its upper layer velocity magnitudes relative to the observational base, with Dietrich et al. (1997) and Welsh and Inoue (2000) possibly being the most realistic published results in this regard until very recently, please see Oey and Hamilton (2002a,b), Oey and Lee (2002), Ezer et al. (2002, 2003), and Oey et al. (2003). Wallcraft (1985, 1986) carried out important examinations of parameter space (typically called sensitivity studies) with a variety of two-layer numerical experiments on the general circulation of the GOM, involving horizontal grid spacing of both 10 and 20 km, and horizontal eddy viscosities from 300 down to 50 m^2s^{-1} . Some of these numerical experiments yielded qualitatively realistic current features, as discussed in Chapter 2 and Appendix C. HT8082 pointed out that time variations in the deep inflow or the vertical current shear in the LC as it flows

through the Yucatan Straits could have a greater dynamical effect on LCR eddy shedding than temporal fluctuations in the upper ocean inflow. For example, a sufficiently strong deep inflow can prevent eddy-shedding by forcing flow along depth contours in a port-to-port mode (eddy shedding can be inhibited by overly large horizontal eddy viscosities as well). The nature and influence of deep currents in the vicinity of Yucatan Straits has proven to be an interesting topic (Maul, 1976, 1977; Maul et al., 1985; Oey, 1996, Sheinbaum et al, 2002; Bunge et al., 2002; Ezer et al., 2002, 2003), and a needed focus of future work. It has also been found (originally noted by HT8082) that time dependent upper layer inflow that is surface trapped (recognized observationally by Cochrane, 1972) might have an influence on realistically modeling the Gulf. Oey (1996) and Vukovich (1999) and Welsh and Inoue (2000) are recent examples of interesting model-data inter-comparisons on the general circulation in the GOM, please also see Lee and Mellor (2003), and Oey et al. (2003). Numerical models are powerful tools, but with limitations, and their oceanographic utility is a strong function of how numerical experiments are formulated and applied, tested and evaluated, and improved upon. This type of application as emphasized in this review envisions a sequence of numerical experiments where application specifications (resolution, boundary conditions, forcing functions, and parameterizations of mixing processes) are varied in order to identify choices of realistic as well as unrealistic performance relative to the database. This type of feedback, which should also consider diverse published results, hasn't been at the forefront of research in physical oceanography in the past few years (but please see Hurlburt and Hogan, 2000, for example). Computer and human resources are the limiting factors at this time (mid-2003).

Figure 1-15: A qualitative illustration of the instantaneous interface deviation, based on results from a two-layer numerical experiment at a particular time, source as noted on this map. Positive (red) values are indicative of anticyclones (H denotes a high), blue for cyclones (L denotes a low). Possible products of the collision or interaction of an incoming ring with the westernmost boundary in the Gulf are indicated by H' and L'.

The first journal publication that exhibited numerical model results containing an anticyclone/cyclone pair as collision products in the western Gulf (Figure 1-15) was by Hurlburt (1984, please see his Figure 2, and also Wallcraft and Thompson, 1984). In Figure 1-15, based on the sources cited in the previous sentence, upper layer anticyclones are denoted by red lines (with a label H for high) and cyclones are in blue (with an L for Low). As pointed out by a variety of authors (Wallcraft and Thompson, 1984; Wallcraft, 1985, 1986; Thompson, 1986) as well as Hurlburt (1984), the large incipient LCR in the eastern and central Gulf in Figure 1-15 is approximately like the canonical observation of a similar kind of feature by Leipper (1970), presented later in this review as Figure 2-12, please also see Figures 1-10 and 1-11. Although a few anticyclones and cyclones were present in earlier numerical experiments by HT8082 in their idealized rectangular domains, model runs in the improved domain in Figure 1-15, looking like the GOM,

contained a more interesting and numerous population of diverse eddies. Numerical experiments at 10 km horizontal resolution by Wallcraft (1985, 1986) improved this picture by a factor of two or so (Figures 2-49, 2-50, 2-64, C-6 and C-7). A map of this new domain was presented by Wallcraft (1985, his Figure 7). Note that the minimum depth in this domain is 500 m, a very crude approximation for the continental shelves and upper continental slope in the Gulf (which may lead to an overestimate of the population of eddies in some sense, especially on the model continental shelves, please see Chapter 2 and Appendix C for further discussion). Northward drift and LCR decay upon reaching the western boundary in the Gulf was initially noted in model results by HT8082, please see Figure 2-69. It is now understood that the westernmost Gulf is the site of LCR interaction with the continental slope and shelf that yields cyclones as collision by-products. Possible collision products are identified by an H' and L' respectively in Figure 1-15. In qualitative analogy to similar results based on observation by Biggs et al. (1996), and presented later in Chapters 1 and 2, there are also possible eddy-eddy interactions in view in Figure 1-15 with a cyclonic feature in the western Gulf having possibly participated in cleaving a LCR into the two anticyclones there (H and H').

Hurlburt (1986, in his section 5.5) analyzed numerical model results for the GOM in which frontal eddies were present (but not well resolved at the 20 km grid spacing typically used at that time), at the lowest horizontal viscosity used. Please note that these results were previewed by Hurlburt (1985). As the eddy viscosity was decreased in a sequence of numerical experiments, meanders and cyclonic eddies (mostly the former) appeared on the outer boundary of the Loop Current. According to Hurlburt (1986, pp. 2380-2381), eddies or meanders were observed to form on the cyclonic shear side of the LC, southwest of its center, and propagate around the Loop, some nearly to the outflow port, at about 15 km/day, perhaps in general analogy to the observational results by Vukovich et al. (1979a) and Vukovich and Maul (1985). These cyclonic eddies were formed about every 20 days, but only during a few months prior to an eddy shedding event (when the model-derived LC had bent sufficiently over toward an east-west model configuration). Hurlburt (1985, 1986) had noted that two types of cyclones tended to be formed in these numerical experiments, one highly time dependent type of cyclonic eddy/meander on the western side of the LC and another more stationary structure on the eastern side, in the southern sector of his domain (possibly to some extent as initially described by Cochrane, 1972). Hurlburt (1985, 1986) considered the role that might be played in LCR formation by a mixed barotropic-baroclinic instability. The important study by Oey (1996, hereafter O96) using a numerical model in process mode considers several features of the circulation dynamics in the GOM and includes examples of the role cyclones might play in the LCR separation process, although the mechanism (perhaps connected to a baroclinic instability, with the composite ring separation process involving a mixed instability) of formation and amplification of these cyclones probably still needs (much) more attention. Interesting cyclonic features concentrated below the sea surface (with rather long time scales perhaps) are present in some of the maps of model results presented by O96, and these cyclones may play a role in model equivalent LCR separation, which does not clearly reflect the influence of frontal eddies. Figures 1-

16 and 1-17 are schematics of some of the model data presented by O96 (his Figure 5). Figure 5 in O96 contains a selected time series of maps of near-surface (the uppermost model level depth) velocity vectors and upper layer (top 750 m) transport stream function contours for one of the numerical experiments (called C2) that he examined. Frames (a) and (b) at model times 2915 and 2970 days in Figure 5 by O96, as will shortly be presented in Figures 1-16 and 1-17, provide an example of how model-derived cyclones might combine to influence the model-related pinch-off of a current ring from the LC in Figure 1-17. It seems notable that Oey (1996) as well as HT8082 found LCR separation without resolving frontal eddies, as was also the case in the Sturges et al. (1993) results, perhaps suggesting more than one model-related mechanism for the composite process of LCR formation, possibly with different cyclonic interactions, and related to the westward drift of the "top" of the LC. In general however, extensive northerly penetration of the model equivalent LC (up to the continental slope/shelf break in the northeastern Gulf) is not seen in any of the O96 results (or model results from Sturges et al., 1993), but is present in the Wallcraft (1985, 1986) results. Other examples of the maps contained in the composite Figure 5 in O96 will be discussed in Chapter 2 and Appendix C. The association of cyclones with the separation process is more clearly seen in the transport stream function maps in the model results by O96, relative to maps of surface current vectors. The presence of very few cyclones in the surface layer may be a characteristic of numerical experiments that are not sufficiently energetic and/or don't adequately resolve smaller cyclones (the 20 km grid spacing used by O96 and others is probably too large for this purpose), although Hurlburt (1985, 1986) began to resolve small meanders on the Loop Current Boundary Front at 20 km horizontal resolution, but by using a comparatively low horizontal viscosity and favorable inflow angle.

Figure 1-16: A schematic illustration of the principal upper layer circulation patterns/features present on a stream function map at the noted model day for the particular numerical experiment listed. The label A in red indicates an incipient LCR, and a remnant anticyclonic ring is denoted by R. The labels WCF in the western Gulf and ECF in the eastern Gulf denote Western Cyclonic Feature and Eastern Cyclonic Feature, respectively.

Figure 1-16 is a schematic of the stream function field in Figure 5 by O96, frame (a), at time 2915 days. In Figure 1-16, cyclonic features are shown in blue and anti-cyclonic features in red. There is a warm core ring (labeled A) that has just begun the necking down process and has a cyclonic feature on either side. A previously separated warm core ring labeled R for "remnant" is in a typical position on and near the slope-rise system in the western Gulf. Figure 1-17 is a schematic of the upper layer stream function by O96 for his Figure frame 5(b) at time 2970 days for model run C2, 55 days after Figure 1-16. In Figure 1-17, the cyclonic features on either side of the LC have possibly participated somehow in the detachment of the LCR which is in the process of separation from the LC and labeled A in Figure 1-16. Please note the small cyclone near the throat and compare

with figures of similar type in Chapter 2 and Appendix C. There are two anti-cyclonic remnants labeled R in the western Gulf in Figure 1-17. The large scale cyclonic feature in the western Gulf can be contoured in more than one way, either by emphasizing the larger scale of these cyclonic features or of the individual cold core eddies. The results of a cleavage of an anticyclone by these cyclonic features may be present in Figure 1-17. It is easier to identify cyclones in the velocity vector maps for the model level at 150 m (Oey, 1996; his Figures 18 and 19) than at the surface, and the transport streamfunction for the upper 750 m depth range is best for identifying cyclones from the results presented by O96, which may imply that these cyclones are primarily deep features. There are general qualitative similarities between the distributions of cyclonic and anticyclonic features in Figures 1-15, 1-16, and 1-17. Figure 1-15 is based on a two layer numerical experiment, and Figures 1-16 and 1-17 are taken from a much more highly vertically resolved sigma coordinate model run. These figures also possibly have some features in qualitative resemblance to a variety of SSH maps including results by Biggs et al. (1996) in Figures 1-18 and 1-19, please also see Figures 2-73 through 2-76.

Figure 1-17: A schematic illustration of the principal upper layer circulation patterns/features present on a stream function map at the noted model day for the particular numerical experiment listed. The label A in red indicates an incipient LCR, and a remnant anticyclonic ring is denoted by R. The labels WCF in the western GOM and ECF in the eastern GOM denote Western Cyclonic Feature and Eastern Cyclonic Feature, respectively.

HT8082 found a strong sensitivity to the vertical shear (as measured by the difference between the upper and lower layer transport, the total was fixed) that they stipulated for the transport (current profile) at the Yucatan Straits. O96 found that eddy shedding by the Loop Current was, in his model results, explicitly associated with vertical shear (in transport) in the LC System near the Yucatan Channel, please see Chapter 4 (Figure 4-20, figure 6 by O96) and Appendix C in this regard. O96 clearly made the case for using an extended domain in modeling the GOM (please also examine in this regard Murphy et al., 1999, and Oey et al., 2003). However, the specific choices to be made in this context, along with the selection of the boundary conditions applied, still need more numerical experimentation. That is, it is not yet clear which regional boundary conditions, or where they should be specified or measured, are best suited for modeling the GOM. It is clear that O96 demonstrated that upstream conditions beyond the Yucatan Channel may be involved with LCR shedding, in some analogy to observationally based results by Maul (1977, 1978) and Maul et al. (1985), recently also verified by Bunge et al. (2002). Sensitivity studies on various boundary conditions for diverse boundary location choices, including basin scale, are needed. O96 demonstrated that specifying a time mean Yucatan Current as boundary conditions constrains the model solutions, but having boundary conditions in the Cayman Sea that are not consistent with the data base can be an important restriction as well. The results presented by O96 in his Figures 5 and 6 and the

accompanying discussion and analysis are an interesting point on the curve with respect to the contemporary perspective for the Loop Current and its Eddy Field. However, there are features in model run C2 by O96 that may deviate notably from the observed picture. For example, the upper layer currents in Figure 5 from O96 are weak compared to observation, perhaps by a factor of 2 or so, and frontal eddies were not present in the model-derived results. In addition, Figure 6 by O96 indicates an average ring separation interval that is short with respect to that observed by about 30 - 40%. Dietrich et al. (1997) and Welsh and Inoue (2000) appear to have obtained some of the strongest currents present in numerical experiments, along with more recent results by Ezer et al. (2002, 2003) and Oey et al. (2003), please see also Wallcraft (1985, 1986). The most recent sets of model results available (Ezer et al. 2002, 2003; Oey and Lee, 2002; Oey and Hamilton, 2002a,b; Wang et al. 2002; Oey et al., 2003) will be considered in Chapters 2 and 4, along with Appendix C). These studies represent serious extensions of a community ability to develop increasingly realistic models of the circulation in the GOM. A separate series of model related studies were carried out for the Gulf in the 1990's that were pointed toward developing a predictive capability, under the sponsorship of the U. S. Minerals Management Service. The various components involved (which will be examined in this review, but relative to predictive capabilities only in Appendix C) constituted a wide ranging set of projects including both model data intercomparisons and sensitivity studies, and was managed by Dynalysis of Princeton (Herring et al., 1999). Chapter 2 also contains in its later sections a summary of the general features of the circulation in the western GOM, taken to be roughly the area west of a line from the mouth of the Mississippi River to the Yucatan Peninsula (Figure 1-1). Warm-core rings interact strongly with the topography associated with the continental slope and rise in the western Gulf (Brooks et al., 1984; Hurlburt, 1984; Lewis and Kirwan, 1985; Smith, 1986; Vidal et al., 1992, 1994, 1999; Vukovich and Wadell, 1991), often forming collision products consisting of a cyclone/anticyclone pair, with the anti-cyclone smaller than the original LCR. Anticyclones were observed to coalesce with each other by Kassler and Sturges (1981), Lewis and Kirwan (1989), and Berger et al. (1996), please see Chapter 2 and Chapter 4.1. Welsh (1996, in the vicinity of her Figure 17) describes the merger or coalescence in her model results of a new incoming LCR with an older anticyclone in the northwest Gulf. Biggs and Mueller-Karger (1994) pointed out that one or more anticyclonic circulation features are generally present in the western GOM at a given time, often associated with one or more cyclonic circulation features, as discussed further later in this review. Biggs et al. (1996) recently examined the nature of the eddy field in the western GOM based on satellite altimeter data. This investigation demonstrates clearly that the Gulf of Mexico west of the LC is rather densely populated by both cyclonic and anti-cyclonic eddies (Elliot, 1979; Hamilton, 1992, 1998; Hamilton et al., 1999, 2002; Indest, 1992), actively interacting with each other, with cyclones splitting anticyclones (Biggs et al., 1996).

Figure 1-18: A schematic map of the population of cyclonic (blue) and anticyclonic (red) features in the western Gulf based on satellite altimeter data for the indicated time interval. The labels WCF in the western Gulf and ECF in the eastern Gulf denote respectively, Western Cyclonic Feature and Eastern Cyclonic Feature.

An LCR named Triton (and denoted by a T in Figures 1-18 and 1-19) was observed to detach from the LC in August-September 1991 (Biggs et al., 1996). Beginning in April-May 1992, T began to be tracked using a sequence of SSH maps by Biggs et al. (1996), and was observed to collide with the continental slope-rise system in the western Gulf (schematically rendered in Figures 2-73 and 2-74). The next LCR to detach from the Loop Current after eddy T, called eddy U, began to approach the western Gulf as T was in the decay process, in the time frame June to September 1992 (Figures 2-75 and 2-76). Figures 1-18 and 1-19 are schematics taken from a time sequence of maps based on the satellite altimeter data presented by Biggs et al. (1996), further showing the evolution of various anticyclonic and cyclonic eddy distribution patterns (starting in time after the sequence of events in Figures 2-74 through 2-76). Each map is based on “averages” over a satellite altimeter cycle of about a month; cyclones are depicted with blue contour lines, anticyclones or warm core rings by red lines. Contour intervals are arbitrarily chosen to convey a general qualitative message. In Figure 1-18, Triton (T) is diffuse, but in Figure 1-19 it has recombined in the southwestern Gulf. In Figure 1-18, covering the time interval September to early October, 1992, an additional (after Triton) incoming warm core ring (to the western Gulf, previously labeled U in Figure 2-76) is in the process of being pinched down into two pieces, now labeled u and v in Figure 1-18, by cyclonic features prominently located on either side of it. There are new anti-cyclonic features present in the northeastern and southwestern Gulf in Figure 1-18, relative to the previous altimeter data cycle (Figure 2-76), and now Triton (T) is barely a remnant. Figure 1-19 shows the products u and v, after the dipole in Figure 1-18 was cleaved by cyclones (perhaps amplified frontal eddies). Note the qualitative similarity of the configuration in Figure 1-19 to that in Figure 1-17. The features marked ECF (Eastern Cyclonic Feature) and WCF (Western Cyclonic Feature) in Figures 1-18 and 1-19 suggest a possible similarity of this cyclonic feature with its analogues in Figures 1-16 and 1-17 (farther into the western Gulf perhaps), labeled in a similar way. Of course, many SSH maps based on altimetric data have qualitatively different distributions of cyclonic features in the western Gulf relative to the figures just shown. Looking at SST maps (in Chapters 2.3 and 4.1, for example) yields the impression that at some times LCR's have frontal eddies on their boundary that can amplify to cleave reattached LCR's as well as cleave LCR's into pieces along their propagation path. In Figure 1-19, eddy T also appears to have coalesced with the anticyclone in the southwestern Gulf in Figure 1-18.

Figure 1-19: A schematic map of the population of cyclonic (blue) and anticyclonic (red) features in the western Gulf based on satellite altimeter data for the indicated time interval. The labels WCF in the western Gulf and ECF in the eastern Gulf denote respectively, Western Cyclonic Feature and Eastern Cyclonic Feature.

END OF SECTION 2, OF CHAPTER 1, LAST UPDATED 21 NOVEMBER 2003.