CHAPTER 1: AN INITIAL SURVEY

SECTION 1

This is the initial chapter in the first of two review volumes that summarize the basic characteristics of the primary circulation features in the Gulf of Mexico, considering deep water flow patterns as well as coastal currents, and including interactions between these two types of flow regimes. Volume I emphasizes the low frequency and large-scale or general circulation in the deep Gulf of Mexico, offshore of flow regimes linked to continental margins, and focuses on long-period processes, taken to mean roughly weekly to monthly average and longer time scales. Coastal circulations (flows associated with continental shelves and perhaps extending offshore over the continental slope) are the focus of Volume II, which considers order days to a couple of weeks variability as well as longer time scales. In Chapter 1, which is an initial (preliminary) survey of the material contained in Volume I, the reader will be exposed to most of the circulation features and processes to be encountered throughout this review volume, as well as given an explanation of how the review is organized. Chapter 2 (on the general circulation of the Gulf of Mexico) contains further discussion of important circulation process issues, as well as many details relative to Chapter 1. Interactions between the general circulation in the Gulf of Mexico (GOM, or perhaps just the Gulf) and the flow patterns in the vicinity of its continental shelves will be initially explored in Chapter 3 of Review Volume I, and considered in detail in Volume II. In Volume I, Appendix A contains a sequential account of almost all available publications (which are listed in Appendix B) for those interested in a historically-linked bibliographic summary of what is known about the deep-water circulation in the Gulf of Mexico, as well as some associated topics. There is also an Appendix (C) on the relation between observations and numerical model results, a topic emphasized throughout this review. In Volume II of this review, there are similar appendices for coastal circulations. Appendix D is focused on providing a survey of the global and basin-wide flow context in which the general circulation of the Gulf of Mexico is set, another innovative feature of this review. The final section of Appendix D (D.4) contains a glossary that considers selected basic information and concepts. Generally speaking, an effort has been made (as indicated in the ABSTRACT) to prepare chapters and appendices that stand more or less alone, which may involve noticeable repetition. Most chapters and appendices will end with a brief synthesis or summary, and Chapter 4 contains such remarks for the composite review, as well as being a locus for the discussion of very recent publications, along with state-of-the-art considerations. Chapters and Appendices in this review have been split into sections for ease in downloading. Each of these sections is described briefly at their start, in analogy to the following paragraph.

Organizational Notes for Chapter 1 are contained in this paragraph: Chapter 1 is an introductory survey of topics covered in detail later in the review, along with some historical material. 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. Section 1 of Chapter 1(Chapter 1.1) contains a preamble that considers mostly general background information, including some historical remarks as noted above, and then moves 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. 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 important processes in the western Gulf. Section 3 (Chapter 1.3) involves an initial look at coastal circulations and their interactions with the flow characteristics 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 1.1 was last updated on 17 December 2003, and there are about 22 pages and 14 illustrations involved (Figures 1-1 through 1-14). Page and figure numbering is by Chapter, not Chapter Sections. Figures follow the corresponding text sections.

The approach taken in this review is to discuss results based on a variety of methods, so that descriptive generalizations and data-based conclusions will be considered along with both analytical inferences and numerical model results. Summaries and syntheses of a broad spectrum of publications are presented, and new interpretation and perspective are included. In line with the anticipated interests and background of much of the review audience as well as my natural inclination, mathematical manipulations will not be presented, although a few analytically oriented references are cited for the interested reader. Theoretical ideas will be used to guide interpretation and synthesis, and efforts will be made to discuss in general terms the most important dynamical processes, and occasionally identify leading order (first approximation) dynamical balances, but not worry much about higher order effects, for which the interested reader may refer to the publication base. Numerical model results in process mode (numerical experiments), will be extensively used in this review to examine mechanisms and processes, to extend the applicability of more idealized analytical models in some cases, and in interpreting results from (typically) limited data sets. There exist a variety of numerical models [perhaps a panoply given the recent explosive growth in this arena, please see, for example, Haidvogel (1998)], and there are various ways in which numerical models may be used, including in prediction mode. Process mode results from numerical models are discussed throughout the review, prediction mode is considered to some minor extent primarily in the last section of Appendix C (C.4). This review does not consider model formulation, but emphasizes application and intercomparison with observations, especially in the light of sorting out basic mechanisms and improving model performance. The issues involving application of numerical models to specific regions of the ocean can be tricky. This comment applies not only to basin-scale and ocean domains, but also marginal seas like the GOM and/or the Caribbean Sea, as well as coastal and estuarine circulations. A definite effort is made in this review to provide a practical view of what to expect when utilizing numerical studies at this time (mid-2003). The large-scale circulation of the GOM was the subject of ground breaking numerical modeling studies in the early 1980's (Hurlburt and Thompson, 1980, 1982). These results were amplified and extended significantly by Wallcraft and Thompson (1984), Hurlburt (1984, 1985, 1986), Wallcraft (1985, 1986), and Thompson (1986). More recent applications yielding numerical results in process mode for the Gulf of Mexico may be found in Sturges et al. (1993), Oey (1995, 1996), Welsh (1996), Deitrich et al. (1997), Welsh and Inoue (2000), Oey and Lee (2002), Wang et al. (2002), Oey and Hamilton (2002a,b), Ezer et al. (2002, 2003), Oey et al. (2003), and Chérubin et al (2003). Some success with respect to modeling the overall transport characteristics of the general circulation in the tropical and subtropical regions of the North Atlantic Ocean in which the GOM is embedded (and therefore responsive to), have been published by Thompson et al. (1992), Townsend et al. (2000), Fratantoni et al. (2000), and Johns et al. (2002). Please also see, for example, Bryan and Smith (1998), Chassignet et al. (2000), Chassignet and Garraffo (2001), Chérubin et al (2003), Holland and Bryan (1993), Hurlburt and Hogan (2000), Smith et. al. (1999), Willebrand and Haidvogel (2001), and Willebrand et al. (2001) for recent views of numerical model results involving the North Atlantic Basin. Numerical models are powerful tools, but their utility is a strong function of how they are applied, tested, interpreted, and improvements made. There is an unfortunate recent tendency to assume that more or less any numerical model application will be successful and take place without significant departures from the database, even making this kind of claim can take place with a comparatively minor expenditure of resources. Vukovich (1999) is a recent example of a potentially very useful model-data intercomparison for the general circulation in the Gulf, please also see Niiler (1999) for similar kinds of results on the coastal circulations in the northwestern Gulf. However, the circuit needs to be closed by implementing changes or improvements to model applications, in order to rectify the problems found. So far, the general circulation in the deep GOM as well as its coastal circulations have proven more difficult (perhaps much more) to model well than was anticipated (this is true in varying degrees for ocean modeling in general). On the other hand, in the last year or so(as of mid-2003), several new numerical experiments involving the GOM have become available, please see Chapter 2.4, Appendix C, and Chapter 4 for more extensive discussion. Very serious sensitivity studies on the results of their two-layer model of the GOM were routinely carried out by Hurlburt and Thompson (1980, 1982), emphasizing to some extent the significance of the horizontal viscosity, but also discussing many other model application choices. Wallcraft (1985, 1986) demonstrated the utility of 10 km as opposed to 20 km horizontal resolution for numerical experiments of an updated version of this two-layer model for the GOM. Schmitz and Thompson (1993) found that doubling the horizontal resolution (to 10 km from 20 km) in a two-layer model of the mid-latitude North Atlantic Subtropical Gyre led to an eddy kinetic energy pattern that was twice as realistic in amplitude as well as having a longitudinal and latitudinal structure more in line with the database. This is a qualitatively general result, that is ~10 km horizontal grid spacing is mesoscale eddy resolving, 20 km is not [please see for example, Bryan and Smith (1998) and Hurlburt and Hogan (2000)]. If frontal eddies are important in a given domain, and this is definitely the case in the Gulf, then 5 km or even smaller horizontal grid spacing may be required. It takes ~ 5 km station spacing or less to adequately define the 15-20 km wide zone of high horizontal shear (cyclonic), which is also associated with comparatively high vertical shear, on the left hand side of the Yucatan and Loop Currents (looking downstream). This kind of zone of intense shears is a general property of the Gulf Stream in most locations (please see Chapters 2 and 4 and Appendix D. Oey (1996) carried out important sensitivity studies on the horizontal viscosity specification, and on boundary conditions, and this study in my opinion contains the most important numerical model results published in the 1990's on the general circulation of the Gulf.

In this review, climate models are not considered seriously, the priority is on eddy-resolving studies with emphasis on the Loop Current and on the mesoscale eddy field in Gulf of Mexico. However, crucial boundary condition issues are perhaps more practically implemented on a larger scale, and water mass conversions addressed in climate models are important in this regard. At this time (mid-2003), the use of either extended domain or basin scale numerical models to provide boundary conditions for the Caribbean Sea and Gulf of Mexico is a research topic at the forefront of the field, limited however by the availability and utility of regional and basin scale model results that have been adequately tested. Numerical experiments in conjunction with the data base have been used in examining properties of the large amplitude mesoscale eddy field associated with western boundary current regimes throughout the World’s Oceans for about 20 - 30 years [for the Gulf Stream System, please see for example, Holland and Lin (1975a,b), Holland (1978), Schmitz and Holland (1982, 1986), Schmitz and Thompson (1993), Holland and Bryan (1993), Schmitz (1996a,b), and Hurlburt and Hogan (2000), and please refer to Appendix C for more discussion]. The Loop Current and its eddy field, which are associated with mixed barotropic and baroclinic instabilities [originally discussed in idealized terms in detail by Hurlburt and Thompson(1980, 1982) for the Loop Current in the Gulf, an instability mix is also typical for mesoscale eddies throughout the oceans], are one component of the Gulf Stream System. The latter is the major contribution to the North Atlantic Western Boundary Current Regime (Hogg and Johns, 1995), containing both wind-driven and thermohaline components (Appendix D), along with eddy-driven circulations (recirculations). In the Gulf of Mexico, the numerical model results by Hurlburt and Thompson (1980, 1982, and others) were compared with general features of the database as available. However, model data intercomparisons of more recent vintage, involving specifically acquired observations in the Loop Current Regime, have not yet been carried out as extensively as has been done for many other locations in the Gulf Stream System. The data base needed to adequately guide and evaluate numerical model applications involving the Loop Current System, and sort out the origin of its eddy field (involving frontal eddies and cyclones as well as anticyclones), simply does not exist. However, at this new time measurements are just becoming available [Bunge et al. (2002); Candela et al. (2002); Scheinbaum et al. (2002); Welsh (2003, pers. comm.)], please see Chapter 4. In addition to considering results obtained with a variety of methods, this review also uses comparative mode where possible. This essentially means that publications on areas in addition to those specifically concerned with the Gulf of Mexico will be readily examined. Comparative mode is usually a good idea, and in this regard please see, for example, the discussion of results due to Ichiye (1962) later in this introductory survey as well as in Chapter 2 and Appendix A. One can hopefully learn from both successes and mistakes in the past, to some extent regardless of location, and often save time and effort. However, extrapolation has to be approached with caution, and there is no practical way around obtaining an adequate database and idea-base for any specific region or process(es), and the oceans can be notably geographical in this regard.

A few smoothed depth contours for the Gulf of Mexico (GOM) along with a set of regional names are contained in Figure 1-1. Included in this figure is an example configuration (in red) of the Loop Current that is flowing more or less directly from the Yucatan Straits to the Florida Straits (sometimes called the port-to-port position or mode) with a restricted northerly penetration (to ~ 24°N) into the eastern Gulf. An example of an extended northerly penetration (to ~ 28°N) of the Loop Current into the GOM is also shown schematically in Figure 1-1(in blue). It is useful and typical to discuss the circulation in the GOM (often referred to as the Gulf when the context is not ambiguous) in terms of an eastern Gulf and a western Gulf, as indicated in Figure 1-1 (boundary at 90°W, and labels in green). This choice is arbitrary, but historically motivated by the structure of the Loop Current System as well as by meteorological patterns and the topographic/geographic configuration of the Gulf. Looking at Figure 1-1, the Loop Current (LC) enters the Gulf through the Yucatan Straits (where it is called the Yucatan Current) and exits through the Florida Straits (and while flowing through these straits and along the east coast of the United States south of Cape Hatteras it is called the Florida Current). The LC occupies the eastern Gulf and sheds comparatively large anticyclonic or clockwise rotating warm core current rings, as well as smaller anticyclones, connected to various stages of northerly extension into the Gulf, and these Loop Current Rings or Eddies then propagate into the western Gulf. Cyclones or counter-clockwise rotating cold core current rings of various sizes are involved in the separation of warm core rings from the Loop Current by penetrating across the LC and pinching warm-core rings from it, and are also found throughout the Gulf. The warm-core ring separation process may in addition be associated with an exchange of water between the continental shelves in the eastern Gulf with the LC, as well as an exchange between the Gulf and Caribbean through Yucatan Straits. Chapter 3 considers Shelf-Gulf interactions associated with various coastal ocean regimes (Figure 1-2), with some initial illustrative emphasis on the continental shelf regime (normally taken to be located inside the 200 m depth contour) in the northwestern Gulf are mentioned in Chapter 1.3 and examined further in Chapter 3, because of the comparatively large idea and databases that exists there, along with some numerical model results (Oey, 1995). Names for the continental shelf regimes that will be studied in detail in Volume II of this review, and examined in general terms with respect to linkages with the open Gulf in Volume I, are introduced in Figure 1-2. The LATEX Shelf may also be referred to as the Texas-Louisiana Shelf, and the circulation there can also be referred to as the Louisiana-Texas Coastal Current (Murray et al., 2001). Campeche Bank may also be called the Yucatan Shelf.

Figure 1-1: A map of the Gulf of Mexico, including an arbitrary illustrative example of a port-to-port Loop Current Configuration (in red), as well as an extended Loop Current boundary structure (in blue), along with a few depth contours (dashed) as indicated (in m), and some nomenclature.

Figure 1-2: A map identifying various Continental Shelf Regimes in the Gulf of Mexico.

Ichiye (1962) was the first to suggest that eddies or current rings could be shed from the Loop Current due to hydrodynamic instability processes (discussed throughout this review), and then propagate into the western Gulf and influence the circulation there. His approach was in partial analogy to his previous experiences in studying the Kuroshio Current System off the coast of Japan, and is a prime example of the utility of comparative study. The reader should be aware that eddified Western Boundary Current Regimes exist throughout the World's Oceans, with the Kuroshio Current System in the North Pacific being a partial analogue to the Gulf Stream System in the North Atlantic (Appendix D). Hydrographic investigations typically involve the acquisition and analysis of serial (in a water column) measurements of temperature and salinity as a function of pressure (depth). A map based on temperature observations at 200 m depth, which Ichiye (1962) pointed out would be a first approximation for the circulation pattern in the LC, with flow along isotherms, is presented here in modified form as Figure 1-3. Names for various features and locations are indicated in annotation boxes on Figure 1-3. Figure 1-3 is an example of a horizontal circulation pattern for the Loop Current (LC, as colored in red in the annotation box to the northwest in figure 1-3) in the eastern Gulf based on a historical dataset. Selected portions of the data acquired and/or described by Parr (1935), who was a pioneer of the age of hydrography in the GOM, and used by Ichiye (1962) to examine the structure and the dynamics of the LC, are presented schematically in Figure 1-3. Figure 1-3 shows the LC in a northerly extended mode in the eastern Gulf, containing an internal anti-cyclonic feature, an embedded anti-cyclonic eddy or warm-core ring, labeled in red as "embedded eddy", which may play a role in an eddy separation process, and centered within the LC near 24°N, 86°W. Also shown is a deep penetrative intrusion (as indicated by the color blue in an annotation box), of comparatively cold water from the West Florida Shelf, extending about 150- 200 km into the LC from about 27.5°N to 26°N. This cold cyclonic tongue or intrusion that penetrates a large distance from the east or northeast into and across the LC in Figure 1-3 is probably the earliest observation of this type of feature, first studied next in detail by Vukovich et al. (1979a), please see Rinkel (1971) and Ichiye et al. (1973) for some preliminary observations of cyclones on the boundary of and/or in the vicinity of the LC. These comparatively large, cold-core cyclonic features are emphasized in this review in the context of being an essential component of the observed composite process of separation of warm-core eddies of a variety of sizes from the Loop Current. The segment of the LC that is north and west of the deeply penetrating intrusion in Figure 1-3 appears (in retrospect) to be approaching the necking-down component of the composite process of separation of an anticyclonic ring from the LC (please also see Figure A-6), one of the patterns that have become commonly observed, for example, by Fratantoni et al. (1998). Also annotated on Figure 3 is a jog or meander (comparatively small) just east of the Dry Tortugas (called Eastern Meander in the appropriate box, in blue), first emphasized by Cochrane (1969b, 1972) when at larger amplitude. The boundary or axis of the Loop Current in Figure 1-3 (as indicated by the position of its 15°C isotherm at 200 m depth) extends north to about 28°N, roughly orientated toward the protruding Birdsfoot Delta of the Mississippi River System. This is close to the maximum northerly penetration of the Loop Current, as observed over time. The earliest map (that I have seen) of the large scale circulation of the Gulf that suggests that the LC might penetrate up to the continental slope or shelf in the northeastern GOM was presented by Haupt (1898, please see the discussion in Appendix A.1, near Figure A-2 there).

Figure 1-3: A map showing isotherm contours at 200 m depth (in °C, solid lines) in the eastern Gulf, based on hydrographic data from the 1930's. The dashed line is the 100 fathom depth contour, dots indicate station locations.

There are also present in Parr's data (1935, his Figures 11 and 12; schematically depicted as figures A-3 and A-4 in this review), examples of both a warm-core, salty anticyclone and a tenuously observed warm-core, comparatively fresh anticyclone in the western Gulf, each visually isolated, seemingly cut-off features, probably the first observation of mesoscale eddies in the western Gulf. The warm-core salty ring in the data presented by Parr (1935, his figures 11 and 12) is much better defined by the data (as shown by Nowlin, 1972) than a comparatively fresh ring, please also see Appendix A.1. According to Elliot (1979, 1982), whereas Ichiye (1962) was the first to suggest the formation of large warm core eddies from the LC, often called in this review Loop Current Rings (LCR's), Cochrane (1969b, 1972, with 1969 data) was the first to distinctly observe the separation and westward propagation of an LCR, and to estimate the translation speed [although, as noted in Appendix A and Chapter 2, Nowlin et al. (1968) had previously described a detached eddy found on a cruise in 1967]. Cochrane (1972) was an important publication, also containing a discussion of a mechanism for the formation of Loop Current Rings that involved warm-core eddies being pinched off by two penetrative cyclonic cold-core features between Campeche Bank and the southwest Florida shelf, as discussed shortly in the vicinity of Figures 1-7 and 1-8. Cyclonic features on the northern boundary of the LC, like the deeply penetrating intrusion (perhaps an amplified frontal eddy) in Figure 1-3, also play a key role in the process of pinching off of an extended Loop Current to form the smaller variety of detached anticyclonic current rings (for example, Vukovich, 1995; Fratantoni et al., 1998). The location of the pinch-off position in Figure 1-3 is an example of a cyclonic intrusion from the West Florida shelf across the Loop Current that occurs comparatively far to the north in the eastern Gulf relative to the original view by Cochrane (1972). The latter view was connected to a much larger cyclonic feature (called an "Eastern Meander" by Cochrane, 1972) that penetrated deeply into the LC Eastern relative to the somewhat analogous feature present in figure 1-3. This distinction is discussed throughout this review. Intrusions may also be examples of interactions between the Loop Current and the shelf circulation, a topic of considerable interest for over 20 years now. Please see, for comparatively early examples, all of whom observed relatively small cyclonic eddies near the shelf break in the eastern Gulf: Maul et al., 1974; Maul, 1977; Niiler, 1976; Pauluskiwiecz et al., 1983. Maul (1977) also mapped a couple of deeply penetrating intrusions into the LC, as did Rinkel (1971). Interactions between the eddies shed from the Loop Current and the continental shelf regimes in the western Gulf [for example, the exchange of water described by Brooks and Legeckis (1982)] also remain state-of-the-art research topics at this time (mid-2003). In this review it is suggested that the effects of the flow of water from the continental shelf regimes into the deep GOM, in both eastern and western Gulf regions, often as jets along the outer shelf (perhaps associated with wind or current driven upwelling), perhaps directed offshore over the continental slope in connection with variable topography/geometry, are probably as interesting and significant as the influence of the flows impinging on the continental shelf systems from the deep Gulf, that is, coastal circulations may significantly influence the circulation in the deep Gulf as well as vice-versa.

This review will highlight historical achievements within its various topics. It seems remarkable that just one picture (Figure 1-3) based on data acquired roughly 70 years ago, and published by Ichiye (1962) approximately 40 years prior to the present, could reflect so much of what occurs and is of interest in the eastern Gulf today. Figures 11 and 12 by Parr (1935) that clearly contain a warm-core eddy in the western Gulf (please see Appendix A.1) are also a notable first. Equally remarkable however, is the realization that the comparatively extensive available upper ocean database for the Loop Current System, involving many hydrographic observations in the upper ocean depth range, and involving now a large amount of satellite-acquired Sea Surface Temperature (SST) and Sea Surface Height (SSH) data, are not yet accompanied by much deep data, nor by adequate time-series measurements of currents at a variety of depths, especially compared to the rest of the Gulf Stream System. SST and SSH maps of the GOM taken from satellites are now acquired and made available on a routine basis, and constitute very important complimentary data sources for the Gulf, especially in terms of identifying both eddies and the LC, and as data sets for assimilation into numerical predictions. According to Vukovich (1995), both large and comparatively small warm core or anticyclonic eddies can be separated from the Loop Current, and examples of both are presented in Chapters 1, 2 and 4 in this review. The smaller anticyclones tend to pinch off and separate from the Loop Current at a comparatively northern latitude, and may either decay soon (Vukovich, 1995) or drift toward the western Gulf, interacting with other eddies (cyclones and anticyclones) along their propagation path, and eventually collide with the continental rise and slope and decay there (please see, for example, Elliot, 1979, 1982; Brooks et al., 1984; Kirwan et al., 1984, 1988; Vukovich and Crissman, 1986; Biggs et al., 1996). Loop Current Rings (LCR’s) can impact shelf circulation patterns in the western Gulf, often in conjunction with cyclone formation (please see, for example; Brooks and Legeckis, 1982; Vidal et al. 1992, 1994; Jochens, 1997). Modern results imply a more active role than previously anticipated for cyclones throughout the GOM, including regions in the vicinity of coastal circulations (for example; Cochrane, 1972; Maul et al., 1974; Maul, 1977; Vukovich et al., 1979a; Vukovich and Maul, 1985; Biggs et al., 1996; Fratantoni, 1998; Fratantoni et al., 1998; Hamilton, 1992, 1998; Hamilton et al., 2002; Indest, 1992; Niiler, 1999; Zavalla-Hidalgo et al., 2003). Interactions between coastal circulations and larger-scale currents primarily located in deeper water is a state of the art research topic throughout the World's Oceans right now, as well as in the Gulf of Mexico (Boicourt et al., 1998; Hamilton et al., 2002; Jochens, 1997; Mooers and Maul, 1998; Niiler, 1999; Sahl et al., 1997; Weisberg and He, 2002; Yang and Weisberg, 1999). The continental shelf circulations in the GOM may be said to be in the shadow of very strong currents and/or eddies. There is a qualitative similarity between coastal circulations along the eastern shore of the United States and coastal circulations in the GOM in terms of overall perspective, not necessarily with respect to details, in that, especially for comparatively wide shelves, their inner and middle sections tend to be mostly wind and buoyancy driven, whereas the outer shelves and areas over the continental slope are strongly impacted by the Gulf Stream System [including its eddy field, please see for example; Bane et al., 1981; Boicourt et al. (1998); Hamilton (1987); Lee and Atkinson (1983)]. It is taken in this review to be of potential interest in terms of comparative study for the GOM circulation, that frontal eddies (cyclonic, spin-off, shingles) on the left hand side (on the inshore side) of the Florida Current have been studied intensely from the Florida Straits northward to, say, Cape Hatteras. They are less well studied in the Gulf (Fratantoni, 1998), where they almost certainly (in an amplified stage) play a role in the separation of anticyclonic features, including very large LCR's, from the Loop Current [the latter initially suggested in a specific context by Cochrane (1972)]. Shingles are clearly present in the GOM, but much larger deep cyclonic intrusions (that are comparatively large both horizontally and vertically) into the LC are also observed. Cochrane (1972) pointed out that the process of detachment of an anticyclonic current ring from the Loop Current in the Gulf of Mexico was observed for the first time in May, 1969. According to Vukovich et al. (1979), Cochrane (1972, based on data acquired in 1969) found the Loop Current to be constricted by two large meanders on the LC boundary (the term meander was originally used for cyclonic features in the GOM), with one meander protruding from the Campeche Bank and the other from the west Florida Shelf, a map of such a configuration of the LC is presented later in Chapter 1.1, other examples may be found in Chapters 2 and 4.

Following Welsh (1996, her p. 3), the term eddies will be used in order to refer generally to all of the closed circulation systems found in the GOM, and the large and strong upper level warm core rings formed in the Loop Current System will specifically be called LCR's (Loop Current Rings). In the past several years, the routine availability of high quality altimetric (SSH) data has played a prominent role in identifying observational features of the eddy field in the GOM (for example; Biggs et al., 1996; Hamilton et al., 1999; Leben et al, 1990; Sturges and Leben, 2000). In addition to the large warm-core anti-cyclonic current rings which will be referred to as Loop Current Rings (LCR's), smaller warm-core anticyclonic eddies (for example, Ichiye et al., 1973; Vukovich, 1995; Fratantoni, 1998) and cold-core cyclones (please see, for example, Elliot, 1979, 1982; Vukovich et al, 1979a, Biggs et al., 1996; Hamilton, 1998; Hamilton et al., 2002) also populate the GOM, as is clearly demonstrated by the available SST and SSH maps, many of which are described and discussed in more detail in Chapter 2, please also see Chapter 4.1. Elliot (1979) had an almost unique early on appreciation for the role of cyclones in the Gulf, along with Cochrane (1972). The investigation by Vukovich et al. (1979a) initiated the compilation of important detailed studies of frontal eddies in the Gulf, along with the initial development of a contiguous ring separation database (to some extent also pioneered by Elliot, 1979, 1982), which was continued in a variety of studies (please see for example: Sturges and Evans, 1983; Brooks et al., 1984; Vukovich and Crissman, 1986; Vukovich, 1988a, 1995; Sturges, 1992, 1994; Sturges and Leben, 2000). The most complete separation interval data set that has been published at this time (mid-2003) is due to Sturges and Leben (2000), having benefited dramatically by the introduction of satellite altimeter data in roughly the last decade. Investigations into the nature of the Loop Current and its eddy field in the interval (nominal) from the 1950's to the mid-1970's were primarily based on the acquisition of hydrographic data and its interpretation. Several results based on the hydrographic database are considered in detail in Chapter 2, and discussed as well in Appendix A. Satellite acquisition of sea surface temperature (SST) data became available routinely in the mid-1970's and these observations were used in combination with in-situ data by Vukovich et al. (1979a), followed by Vukovich and Maul (1985), for an important analysis of fluctuations of the "northern" boundary of the LC, in the context of a description of frontal eddies or cold-core cyclonic perturbations on the boundary of the LC. Examples of the basic SST maps that are routinely available on the Internet are presented later in Chapter 1 and throughout this review. A couple of early and highly simplified illustrative examples of SST maps are considered first (in Figure 1-4, and then in several following illustrations).

Figure 1-4 is a map containing schematic versions of the range of configurations (as labeled) of the boundary of the LC as observed in the mid-1970's. These results were presented by Vukovich et al. (1979a), based on satellite-derived SST data, roughly spanning the observed range of LC penetrations into the GOM. Figure 1-4 contains one example of an LC boundary configuration for a typical southerly position occupied by the Loop Current boundary in the eastern Gulf. This port-to-port flow pattern (in green in Figure 1-4) is used to denote current paths that are more or less directly from the Yucatan Channel to the Straits of Florida. Figure 1-4 also contains a schematic of the LC near its most northerly position (in red), up against the 200 m depth contour approximately, just off the Mississippi Delta (to some extent in the vein of Figure 1-3) and perhaps intruding through De Soto Canyon up onto the Continental Shelf. Examples of more recent SST maps with comparatively deep northerly penetration of the LC into the Gulf, similar to the red path for April 1974 in Figure 1-4, have been published, for example, by Hamilton (2000, his Figure 7). In this chapter, the SST map in Figure 1-10 (for 5 March 1998, obtained over 20 years later) exhibits LC penetration almost as far north as the LC configuration represented by the red boundary in Figure 1-4, as well as an overall configuration similar to the map presented by Hamilton (2000) just noted above. Positions of the northern boundary of the LC as far north as shown by the red path in Figure 1-4, or in the map by Hamilton (2000, his figure 7), or in Figure 1-10, although found in model results in the 1980's (Thompson, 1986; Wallcraft 1985, 1986), were not notably present in numerical model results in the mid-1990's (Sturges et al., 1993; Deitrich and Lin, 1994; Oey, 1996; Welsh, 1996), but at this time extended LC configurations and frontal eddies are both being found to some extent at 10 km or better horizontal resolution (Dietrich et al., 1997; Welsh and Inoue, 2000; Oey and Hamilton, 2002; Oey and Lee, 2002; Oey et al, 2003; Hogan, 2003, pers. comm.). Vukovich et al. (1979a) contained examples of comparatively low amplitude meanders, as well as amplifying or developing shingles, along with deeply penetrating cyclonic intrusions, shown (as annotated) in Figure 1-4, please note that many other such figures are exhibited throughout this review. The deeply penetrating cold intrusion on the eastern side of the LC in Figure 1-3 that is based on data from the 1930's has an analogue in 1974, as depicted (and labeled in red) on the eastern side of the extended LC in Figure 1-4. However, the eastern cyclonic feature in Figure 1-4 is at a more southerly position (centered at approximately 24.5°N at its apex) than that in Figure 1-3 (centered at about 26°N at its apex). This type of feature near the southern extremity of the west Florida shelf in Figure 1-4 is in the general area with a similar shape to that first noticed by Cochrane (1969b, 1972), please also see Figures 1-7, 1-8, 1-10, and 1-11. The existence of deep cyclonic intrusions into the LC (please also see Figure 1-9) at a variety of locations on the northern and eastern boundary of the Loop Current is now well documented (for example Vukovich and Maul, 1985; Fratantoni, 1998). Figures 1-4, 1-5, and 1-7 through 1-12 are presented in Chapter 1 as a basic qualitative introduction to the observed range and kinds of configurations of the boundary of the LC, based on SST and SSH data acquired over the past 25 years or so.

Figure 1-4: Schematic illustrations of satellite based SST depictions of the boundary of the Loop Current while in Port-to-Port Mode (in green), and at another time (as indicated) in a more or less maximally northerly extended Loop Current Boundary Configuration (in red). The latter path is deformed as indicated by various flow features as labeled. Selected depth contours (200, 1000, and 3000 m) are depicted by dashed lines.

Vukovich et al. (1979a) presented, in their Figure 1, a history of the location of the boundary of the LC for the non-summer months during 1973-1977. In the summer months, the surface temperature signal associated with the LC and its warm core eddies, along with associated current filaments (shingles, spin-off eddies, frontal eddies along the LC boundary) cannot be adequately mapped by satellite measurements of surface temperature, due to seasonal heating on a larger scale. Throughout the Gulf Stream System, temperatures at 200 m depth are often used to locate current features and eddies, as in Figure 1-3. Figure 1-5 is a schematic of a SST-based frontal or boundary map (for

December 1983) presented by Vukovich and Crissman (1986) showing a recently separated warm-core ring or LCR (Loop Current Ring), with a port-to-port LC just south of the warm-core ring [according to Sturges and Leben (2000), a ring separated from the LC in February, 1984]. In Figures 1-3 and 1-4 the reader was exposed to the approximate extremes of the north-south location of the LC boundary with some developing intrusions, and in Figure 1-5 (based on Figure 1A by Vukovich and Crissman, 1986) the reader is introduced to the configuration of a port to port LC with a newly separated ring to its north that has small shingles or cyclones or meanders along its boundary, associated with warm filaments or streamers. The shingles in Figure 1-5 are reminiscent of those found along the inshore edge of the Florida Current (Fratantoni, 1998; Lee, 1975; Glenn and Ebbesmeyer, 1994a,b). Cyclonic features in the vein of those on the boundary of the LCR in Figure 1-5 are now known to amplify and cleave LCR's into pieces in the western Gulf (Biggs et al., 1996). These features that exist on the LC boundary are called frontal eddies, or meanders, filaments, or shingles, and tend to show up better on SST maps (in the non-summer months) compared to most routinely available SSH maps, probably associated with relative horizontal averaging scales. SSH maps are better for defining the composite eddy field throughout the Gulf, including somewhat larger cyclonic features. A general direction for ring propagation into the western Gulf is denoted by the large red arrow in Figure 1-5. Figure 1-5 exhibits small cyclonic features along the boundary of a warm core ring, associated with warm filaments and called frontal eddies. Many other figures in this review exhibit frontal eddies on the boundary of both the LC and LCR's. please see Rinkel (1971) for early observations of this type of feature.

Figure 1-5: The Loop Current in a port-port location, and a recently detached current ring with meanders and/or filaments associated with frontal eddies along its outer boundary. The red arrow indicates a typical propagation direction for warm-core eddies into the western Gulf.

Maul et al. (1974) identified cyclonic eddies of the smaller type in the eastern Gulf from satellite data, probably the earliest post-Cochrane (1972) effort to study cyclones observationally. Detached cyclones were present in the eastern Gulf in a schematic figure by Ichiye et al. (1973, their Figure 4-1), and a possible cyclonic cold core eddy was detected near the continental slope and shelf break (perhaps trapped there). As an aside, Ichiye et al. (1973) noted that currents near the shelf break off the west Florida Shelf tended to be parallel to bottom depth contours, seldom crossing over the shelf, a key characteristic of most wide-shelf coastal regimes. Ichiye et al. (1973) also pointed out, for the first time I think, that Loop Current Eddies of sizes from 20-30 nautical miles to 150 nautical miles in diameter had been observed. In general terms, frontal eddies on both the LC and LCR boundaries can amplify via instability processes and at finite amplitude may persist, often as cut-off (or approximately so) cyclones. Some of these cyclonic features may amplify to become deeply penetrating intrusions into the LC (Figures 1-4, and 1-7 through 1-12), and participate in the separation or detachment process for warm-core rings (Cochrane, 1972, Vukovich et al.; 1979a, Vukovich and Maul, 1985, Vukovich, 1986; Fratantoni, 1998, Fratantoni et al., 1998; Zavalla-Hidalgo et al., 2003), but the specifics of the mechanism for the development of the deep penetrations are not yet adequately determined. The reader will encounter many maps of the Loop Current in diverse configurations in this review, based on several data types. For example, the SST map in Figure 1-10, based on satellite data taken about 14 years later than the data in Figure 1-5, resembles the LC configuration in the latter qualitatively. The LCR in Figure 1-10 also shows cyclones on both sides of the LC in the process of cleaving a Loop Current Ring from it, please also see Figures 1-11 and 1-12. The maps presented by Vukovich et al. (1979a) and Vukovich and Crissman (1986) were exhibited here in Figures 1-4 and 1-5 as an early-on introduction to the most basic general features of the configurations of the LC and its eddy field. Figure 1-6 is a map based on data developed by Vukovich and Crissman (1986, their figure 6) showing a collage of propagation directions (always a westward component in the mean, typically translating at a few cm/s or km/day) for various individual LCR's. Propagation characteristics are discussed in more detail in Chapter 2.6. LCR's may interact with other warm-core eddies along their propagation path into the western Gulf (for example, a view of eddy coalescence is presented in Chapter 4.1), and will typically collide with the continental slope-rise system there, and eventually decay, with cyclones as possible by-products (please see Figure 1-15 and vicinity). Another type of warm-core eddy decay during propagation, associated with being cleaved into pieces by cyclones (probably originally frontal eddies) is discussed in Chapter 1.2

Figure 1-6: A compilation of observed propagation directions for Loop Current Rings, based on a map by Vukovich and Crissman (1986, their figure 6). Selected depth contours as labeled are depicted by dashed lines.

The separation of warm-core or anticyclonic rings having a variety of sizes from the Loop Current (originally suggested by Ichiye, 1962 to be involved with instability dynamics) is probably the single most intriguing large-scale physical (composite) process occurring in the GOM. Cochrane (1969b; his figure 1, figure 1-7, below) and Elliot (1979) had interesting ideas early on about cyclones and their role in the Gulf, as described in more detail in Chapter 2 and Appendix A. Basically Cochrane (1972) suggested for the first time that large warm-core rings or LCR's could be detached by penetrative cyclonic features on the LC boundary (in Figure 1-7) in the southeastern Gulf [Cochrane (1972) called these features meanders, as did Vukovich et al. (1979)]. Elliot (1979) suggested that cyclones observed in the western Gulf would be formed in the eastern Gulf and propagate westward. Vukovich et al. (1979a), Vukovich and Maul (1985), Vukovich (1986, 1995), Fratantoni (1998), and Zavalla-Hidalgo et al. (2003) have studied these cyclonic features more extensively in the eastern Gulf and came to similar but more detailed conclusions relative to Cochrane (1972), with some differences as well as some new results, as discussed throughout this review. The mechanism(s) for the separation of current rings from the LC were examined in detail with numerical model results (discussed in more detail in Chapter 1.2, as well as throughout this review) by Hurlburt and Thompson (1980, 1982), and numerical experiments where meanders or embryonic cyclones explicitly played a role in this separation process were described by Hurlburt (1985, 1986), please also see Wallcraft (1985, 1986), Dietrich et al. (1997), and Welsh and Inoue (2001). Recently cyclones have received more attention in the Gulf (Hamilton, 1992, 1998; Fratantoni, 1998; Fratantoni et al. 1998; Hamilton et al., 2002; Oey and Hamilton, 2002; Oey and Lee, 2002; Oey et al., 2003; Zavalla-Hidalgo et al., 2003), especially with the advent of satellite altimetry and associated SSH maps (Biggs et al., 1996). Although early studies (Nowlin, 1972) in the Gulf tended to be preoccupied with the large Loop Current Rings (warm core anticyclones, called LCR's in this review), Cochrane (1969b, 1972) was the initial advocate for the importance of cyclonic features in the southeastern GOM (Figure 1-7) with respect to their role in the separation process for LCR's.

Figure 1-7: Depth contours for the 20°C isotherm in the Loop Current System (in the eastern Gulf), based on data acquired in May 1969 on Cruise 69-A-7. Dashed depth contours (in fathoms) as indicated.

Cochrane (1969b, his Figure 1) observed a comparatively large cyclonic feature during the early segment of a cruise in May, 1969 (Figure 1-7), often called in other publications a deep cold intrusion into the LC or perhaps cold cyclonic perturbation (Vukovich et al., 1979a; Vukovich and Maul, 1985). This feature extended from the West Florida Shelf offshore of the Dry Tortugas into the Loop Current between 24° and 26°N [intrusions were called meanders by Cochrane (1969, 1972)]. In Figure 1-7, there is also a smaller (but larger than usual there) meander on the boundary of the LC near Campeche Bank (also called the Yucatan Shelf). These observations were based on the depth of the 22°C isotherm as indicated in Figure 1-7. A clear identification of the significance of the cyclonic intrusion and the meander, marked as such in Figure 1-7, actually occurred in Cochrane (1972), where the subsequent related separation of a warm core eddy and its westward propagation into the Gulf were described. According to Cochrane (1972), the smaller meander on the Campeche Bank side of the LC penetrated deeply across the LC to join up with the larger such feature on the eastern side of the LC to pinch off or detach or separate a warm-core ring from the Loop Current. The actual separation sequence for May, 1969 was later shown specifically by Cochrane (1972, in his figure 4-6), based on two more modest data surveys in late May, 1969, relative to that shown in Figure 1-7 for early May. A general discussion of separation and propagation issues was also based on data from following shipboard surveys, in June and July, 1969, as reflected in Figure 4-4 by Cochrane (1972). The cyclonic intrusion from the west Florida shelf into the Loop Current in Figure 1-3, the earliest observation of this type of feature, occurred at about 1.5° of latitude north of the similar intrusion in Figure 1-7. Penetrative cyclonic intrusions into the LC have now been observed many times at a variety of locations [for example, Vukovich et al. (1979a); Vukovich and Maul (1985); Vukovich (1988a, b); Sturges et al. (1993); Fratantoni (1998); Fratantoni et al. (1998); Zavalla-Hidalgo et al. (2003)]. It should be emphasized that, although the data plotted in Figure 1-7 were published in a report by Cochrane (1969b), it was not until the paper by Cochrane (1972) was published that ideas about the role of this feature in LCR separation were articulated. Figure 1-7 resembles Figure 2-12, which was published by Leipper in 1970, and the latter is often reproduced or cited in the context of a prototypical necking-down configuration for a large incipient warm-core ring, please see Chapter 2.2. In Figure 1-7, there are two cyclonic features pinching down on the throat of the LC between Campeche Bank and the west Florida Shelf off the Dry Tortugas, which will in this review be called the canonical picture due to Cochrane (1972). Pinch-down has also been observed to occur with one deep intrusion from the east or northeast (Vukovich, 1986, 1995; Fratantoni, 1998, Fratantoni et al., 1998), but is not always associated with actual separation. Figure 1-8 is based on maps of the Loop Current boundary configuration presented in their Figure 1 by Vukovich et al. (1979a). The pair of boundary configurations shown in Figure 1-8 is separated by about a month, and constitute an example of pinch-off of a LCR by one or more deep cyclonic intrusions into the LC. According to Sturges and Leben (2000), a ring separation occurred in January 1975. Figure 1-8 qualitatively partially resembles the canonical picture or view described by Cochrane (1969b, 1972), but only clearly so (this is a typical situation, particularly with surface data only) with respect to the meander to the east [called a deep cyclonic intrusion by Vukovich et al. (1979a), labeled in blue as such in figure 1-8]. So far, the separation of an anticyclonic ring from the Loop Current has been described in terms of processes confined to the Gulf of Mexico, that is in local terms. Suggestions have been made however, relative to a potential coupling of the process of ring separation with Loop Current extension into the Gulf involving an exchange of water between the GOM and the Caribbean Sea and possibly the GOM and the Florida Current [Maul (1976. 1977), Maul et al. (1985), Maul and Vukovich (1993), Oey (1996), Fratantoni (1998), Murphy et al. (1999), Bunge et al. (2002), Ezer et al. (2002, 2003), Oey et al. (2003), Chérubin et al. (2003)]. This topic is discussed in some detail throughout Chapter 2 and in Chapters 4.2 and 4.3.

Figure 1-8: Schematic illustrations of satellite based SST depictions of the boundary of the Loop Current for 28 December 1974 (in red), along with 24 January 1975 (in green). Selected depth contours (for 200, 1000, and 3000 m) are indicated by dashed lines.

An example of a large amplitude, deeply penetrating cold tongue or intrusion from the north on the northeast side of the LC is shown in Figure 1-9 [a schematic adaptation of Figure 1A from Vukovich and Maul (1985)]. The cold tongue deeply penetrating into the LC was considered by them to be an amplification of a feature analogous to that labeled "cold perturbation", on the northwest side of the LC as shown in Figure 1-9. The filaments associated with these cyclones or cyclonic intrusions on the boundary of the LC can become quite large, please see Chapter 4.1, and for example Wiseman and Dinnel (1988, their Figure 4). A temperature section extending down to 700 m, collected while the cold intrusion in Figure 1-9 was identified by SST data, defined this cold tongue as a strong and deeply penetrating cyclonic feature, with a 300 m displacement amplitude for the 10 degree isotherm (Figure 1B, Vukovich and Maul, 1985, please see Figure 2-57). Several other cyclonic features (some comparatively small, some representing deep penetrations into the LC) were defined by data and discussed by Vukovich and Maul (1985), where in one case a cyclone was observed to impact a current meter mooring. Vukovich and Maul (1985) pointed out for the first time that the centers of the tongues or intrusions that were observed to be moving seaward from the West Florida Shelf had closed cyclonic eddies at their center. Vukovich and Maul (1985) suggested that the deeply penetrating cold cyclonic tongues develop or amplify on the north side of the LC, one example being Figure 1-9, then move southward on the eastern boundary of the LC, becoming associated with the anticyclonic ring separation process. They also note that in their database cyclonic features may exist on the western boundary of the LC (smaller shingles certainly are present there) but do not grow large until they reach the northern boundary (but please also see Zavalla-Hidalgo et al., 2003; as well as Cochrane, 1972). Pauluskiwiecz et al. (1983) and Vukovich (1986) determined the structure of frontal eddies using in-situ observations. Pauluskiwiecz et al. (1983) compared their results (relatively small eddies) with Gulf Stream Frontal Eddies, a point not considered again until Fratantoni (1998, who coined this term, with abbreviation GSFE's), please also see Glenn and Ebbesmeyer (1994a,b) for a discussion of small and larger frontal eddies in the vicinity of Cape Hatteras.

Figure 1-9: A schematic illustration of the Loop Current Boundary for 20 May 1978, based on satellite-derived SST data. The dashed depth contours are for 200, 1000, and 3000 m respectively.

The type of deeply penetrating cold perturbation in Figures 1-8 and 1-9 was studied further by Vukovich (1986), based on both SST and in-situ data obtained in the spring of 1983. He tracked 3 of these large cold perturbations for a couple of months, during which time they propagated (mostly) southward at 4-10 km/day. They slowed down approaching the southern edge of the west Florida shelf, east of the Dry Tortugas, where they possibly coalesced to form the “Cochrane East Meander” (or Tortugas Eddy according to Fratantoni, 1998). SST data from the spring of 1983 were also analyzed by Brooks et al. (1984), and these results are compared and contrasted with those by Vukovich (1986) along with those due to Vukovich and Crissman (1986) in Chapters 2 and 4. Vukovich (1988b) produced an illustrative description of the formation of elongated cold perturbations offshore of the West Florida Shelf near Dry Tortugas (Chapter 2.5). Deep cyclonic intrusions like those shown in Figure 1-9 may be considered to be amplified frontal eddies that develop into cyclones and play a role in warm core eddy separation, as in Figures 1-10 and 1-12, as in many other such maps presented in this review. Fratantoni (1998) has suggested that embryonic cut-off cyclonic eddies may grow or amplify by coalescence on the southeast side of the West Florida Shelf off Dry Tortugas and near the southern Straits of Florida, please also see Vukovich (1988b). The formation of a cyclonic eddy in the southern Straits of Florida just south of the Dry Tortugas is related to the propagation of frontal eddies around the Loop Current to the southern end of the west Florida Shelf, according to Fratantoni (1998) and Fratantoni et al. (1998), and was found to occur only when the LC is in an extended as opposed to port-to-port mode. An example of the type of maps from which the schematics in Figures 1-4, 1-5, 1-8, and 1-9 were obtained is exhibited as Figure 1-10, a satellite image of sea surface temperatures (SST) for 5 March 1998 on a map of the GOM, as obtained from the Internet (Monaldo, 2002). This figure is a 3 day (nominal) composite, so some clouds have not yet been filtered out, and was downloaded in the summer of 2000 from the site: http: //fermi. jhuapl. edu. avhrr/gm/. Temperatures (in °C) are color coded as indicated with blue relatively cold, and orange comparatively warm. The Loop Current (identified by a black LC label superimposed on the basic color map) in Figure 1-10 appears as dark orange at this time, temperatures being about 27-28°C, a picture which has a schematic similarity to Figure 1-5, (please see Vukovich and Crissman, 1986, for example), maps acquired about 15 years apart. The southerly segment of the Loop Current in the eastern Gulf is approaching port to port mode in Figure 1-10, flowing more or less directly from the Yucatan Channel to the Straits of Florida. To the north, there is a nearly separated LCR (that is lighter orange than, and toward the north-northwest of the LC) in the process of being cleaved by two cyclonic intrusions or cyclones or cold-core eddies. Figure 1-10 is an example of cleavage of a northerly extended LC by a cyclone pair, from the northeast and southwest sides of the LC respectively. This is a vivid image of a current ring in the process of a canonical or prototypical separation phase that may be called “necking down” and/or "pinching-off" from the Loop Current. This typically involves a pair of cyclonic or cold-core features, one from each side at the neck (please see Zavalla-Hidalgo et al., 2003), or at least one larger cyclonic feature from the east (intrusion from the shelf). Figure 1-10, for March 1998, is similar to the SST map for March, 1995 presented by Hamilton (2000, his Figure 7). Please note the filamentous nature of the meanders or incipient frontal eddies on the northern (and perhaps western) boundary of the LCR. Various types of frontal eddies (or shingles, first observed in the Gulf Stream System by von Arx et al., 1955) as depicted in Figures 1-5 and 1-10, are at the forefront of research in the GOM right now (mid-2003). Perhaps the leading unanswered question at this time is how the long cold perturbations or intrusions amplify from the shingle stage as they penetrate deeply into the LC, typically pulling water from the continental shelf system behind them. These features, amplifying cyclonic eddies that penetrate deeply into the Loop Current (not just a comparatively small eddy on the boundary of the LC), are a highlighted process in this review, please see especially Chapters 2.5 and 4.2.

Figure 1-10: Sea Surface Temperature (SST) Map for the GOM on 5 March 1998. Temperatures (°C) are color-coded as indicated by the bar scale to the right. Abbreviations for the Loop Current (LC) at a port-to-port location, along with an incipient Loop Current Ring (LCR), are superimposed on a classical "necking-down" configuration. The deeply penetrating cyclonic tongues illustrated are "pinching the LC and LCR at their throat", and play a role in the separation process.

Some clouds (fuzzy patches with bits of white) have not been filtered out of Figure 1-10 (a 3-day average nominal), seven-day averages (nominal) are more effective in suppressing clouds. Meanders or filaments along the outer edge of the LCR are also labeled in black on the version of Figure 1-10 exhibited on the web-homepage of this review. These meanders and filaments, which may also be called spin-off eddies, frontal eddies or shingles, are well known features in the Florida Current segment of the Gulf Stream System (for example; Lee, 1975; Lee and Atkinson, 1893; Vukovich et al., 1979b), and also play a crucial role in the GOM, especially when amplified (Vukovich and Maul, 1985; Fratantoni, 1998 is a valuable recent review; please also see Zavalla-Hidalgo et al., 2003). However, frontal eddies in the Gulf are probably not identical to the frontal eddies in the Florida Current, in perhaps several respects (different base states and amplified products are possible), as discussed throughout this review. It turns out that an LCR in the position shown in Figure 1-10 (and in Figure 1-5), often reattaches to the LC, and there can be a sequence (for example, Figures 2-34 through 2-42) of detachments and reattachments, many involving a stage like that shown in Figure 1-10, as the LCR propagates westward while still in the proximity of the LC [as initially emphasized by Sturges et al. (1993); perhaps the earliest example of reattachment is shown in Figure 2-1, based on data acquired in the 1950's, Vukovich et al. (1979) refer to a “juxtaposition”]. According to Sturges and Leben (2000), an anticyclonic ring did separate from the LC on 14 March 1998, a week to ten days after the image shown in Figure 1-10. Chapter 2.3 explores the attachment-detachment process in the vicinity of March 1998 in some detail, using SSH as well as SST maps. Insofar as I know, more or less all examples of reattachment are based primarily on surface data, and the deep manifestation of this process has not yet been fully described. However, deep penetrations of energetic isotherm deformations in the vertical by the elongated cyclones that penetrate horizontally across the LC and broker separation of warm-core eddies was emphasized by Vukovich (1986, please see his page 187), as well as by Cochrane (1972). Vukovich (1986) also suggested that frontal eddies could coalesce on the eastern side of the LC. Elliot (1982, his p. 1297) suggested that some of the data that he had examined might be associated with the coalescence of two anticyclonic rings in the westernmost Gulf, one of the first such observations. LCR’s can also be cleaved into two or more parts by cyclones in the western Gulf (possibly involving amplification of frontal eddies present on and around the boundary of LCR's), as well as into by-products (involving cyclones) by collision with the rise and slope there (Biggs et al., 1996; Hurlburt, 1984; Indest, 1992; Lewis and Kirwan, 1985; D. C. Smith, 1986; Vidal et al., 1992, 1994), please see Hamilton et al. (2002) for a summary discussion of cyclones in the vicinity of the continental slope in the northern Gulf. The results by Biggs et al. (1996) were based on a combination of SSH data derived from satellite altimetry and in-situ observations. Readers desiring more information on SSH methodology are referred to Leben et al. (1990), Fu and Cazenave (2001), and their references. At this time (mid-2003) altimetric maps are routinely available (Leben, 2002), and yield an updated or modern view of the Gulf-wide circulation where cyclones are approximately as populous as anticyclones, and the composite eddy field is notably interactive. That is, there now exists a comparatively new and exciting view of the circulation in the Gulf of Mexico, given the satellite altimeter database that has been accumulated over the past several years. In this view, the Gulf is very actively full of various eddies, with cyclones actively pinching off or detaching warm core rings from the LC in the eastern Gulf, and also present on the periphery of ware-core eddies there, and after propagating toward and in the western Gulf, cleaving LCR's into pieces along their propagation paths there. It has been clear for about 20 years that cyclones formed by topographic interactions involving incoming LCR's can play a prominent role in Shelf-Gulf Interactions in the western Gulf (Brooks and Legeckis, 1982; Merrell and Morrison, 1981; Merrell and Vázquez, 1983; Brooks et al., 1984). Figure 1-11 is an example of a map of SSH (Sea Surface Height) based on satellite altimetry in the vicinity of 2 September 1996 with the LC in necking down position. There is also in Figure 1-11 a conspicuous set of weakly attached anticyclonic eddies to the west of the LC, and cyclones to the southwest, east, and north. In Figure 1-11, blue indicates the lowest sea surface heights (SSH), dark orange the highest. Anticyclonic or warm-core rings are highs, cyclones or cold core eddies are lows. There are many examples in the publication base for the Gulf where the LC and its eddy field resemble Figure 1-11.

Figure 1-11: A Sea Surface Height (SSH) Map for 2 September 1996. SSH contours (in cm) are color-coded as indicated by the bar to the right. Cyclonic features tend to be blue, anticyclonic yellow or orange.

As in Figure 1-10, but with a two year or so difference in date of acquisition, one sees in Figure 1-11 a Loop Current in necking down mode, but at a more southerly location, even more analogous than Figure 1-10 was to the Cochrane (1969b, 1972) view, with a LCR being pinched by cyclones (blue) that are in the throat of the incipient LCR near 23°N and 85°W. The cyclones show up as larger in the SSH maps than in the SST Maps, partly because the center of the cyclones exhibit not only the cold core present in the sea surface temperature field, but the composite horizontal extent or size of a cyclone as a region of comparatively low sea surface height. Note that the "weak attachments" between the anticyclonic features in the western Gulf on Figure 1-11 have cyclones seemingly poised at their throats, a typical situation. A main qualitative difference between Figure 1-11 and Figure 1-10 is that the SSH maps (1-11 and others like it) show a comparatively large and dense population of cyclones and anticyclones throughout the Gulf. On the other hand, SST maps yield better pictures of comparatively small scale features (frontal eddies, meanders, filaments) on and around the boundary of the Loop

Current and Loop Current Rings. Another SSH map obtained about 2 weeks after Figure 1-11, Figure 1-12, contains an example of a pinched off LCR, having been separated from the LC by cyclonic features, but not necessarily for the final time, as discussed in detail later in Chapter 2. Compared to Figure 1-11, the cyclones at the neck of the LCR in Figure 1-12, taken two weeks later, have now “fully” separated the LCR from the LC. Sturges and Leben (2000) find that a warm core ring detached from the Loop Current on 14 September 1998, the acquisition date for Figure 1-12. Typically however, there may be some form of reattachment (at least at the surface) to the LC by the LCR until it drifts much farther westward away from the LC. Please note that the weakly connective anticyclonic attachments involving a few features in the western Gulf both in Figures 1-11 and 1-12 can penetrate over a substantial horizontal distance (Gulf-wide). The weaker and smaller anticyclonic features in the western Gulf in Figure 1-12 more or less appear to be in the process of necking-down by cyclones as well, a form of eddy-eddy interaction. The pinch-off locations for the LC in Figures 1-11 and 1-12 in the eastern Gulf between the Yucatan Shelf or Campeche Banks and the southwest corner of the Florida Shelf are very similar to or reminiscent of the Cochrane (1969b, 1972, Figure 1-7) view or "canonical picture". However, the double cyclone pinch-off high-lighted in Figures 1-7, 1-10, 1-11, and 1-12 is not always needed for separation of anticyclones from the Loop Current (Fratantoni et al., 1998; please also see Chapter 2.5).

Figure 1-12: A Sea Surface Height (SSH) Map for 14 September 1996. SSH contours (in cm) are color-coded as indicated by the bar to the right. Cyclonic features tend to be blue, anticyclonic yellow or orange.

So far we have been mostly reconnoitering maps of surface or upper level horizontal circulation and temperature patterns associated with the LC and its warm core eddies, as well as cyclonic features. It is time to take an initial look at vertical structure in the vicinity of the Loop Current and LCR’s, keeping in mind that most of the data available is concentrated near the sea surface. A smoothed upper layer temperature section across the Loop Current (based on XBT data presented by Leipper, 1970) is shown in Figure 1-13. XBT's (Expendable Bathythermographs) are instruments that quickly acquire temperatures as a function of depth while a ship is underway. The thermal structure of the LC, as is true for sections across the Gulf Stream in general, is characterized by plunging isotherms, to the right looking downstream, indicative of high vertical shear in the horizontal current pattern (geostrophic balance at zero order, please see Appendix D). Therefore, at some level, often but not always the sea surface, one expects comparatively high horizontal currents. In Figure 1-13, selected isotherms indicated by the numbers near the contours (temperatures in degrees centigrade, °C), are shown for the upper 250 m or so [older bathythermograph (BT) data typically penetrate down to only about this depth]. The bowl shape of the isotherms in Figure 1-13 is characteristic of a warm-core eddy or LCR as well as the LC. Other temperature (and salinity) sections across the LC and its Rings that extend deeper in the water column will be presented in Chapter 2, primarily, but not always, in the upper 1000-1500 m depths. There is a relatively sparse data base in the vicinity of the LC (as well as in the Gulf and Cayman Sea in general) at depths from several hundred meters to the bottom (about 3500-3600 m on the abyssal plain in the GOM).

Figure 1-13: A smoothed temperature section across the upper levels of the Loop Current.

Figure 1-14 is one example of the vertical structure of the horizontal currents as observed using XCP (EXpendable Current Profiler, electromagnetic sensors) techniques in an LCR in the eastern Gulf (Cooper et al., 1990). The XCP observations also provide information regarding relative currents. What is observed is the difference between the horizontal current at the depth of measurement and the vertically averaged current over the water column (Sanford et al., 1982). This "calibration factor" is often taken to be small, but is not always. Figure 1-14 is a plot of speed against depth (red line) and direction against depth (blue line) in a smoothed representation of the data from Cooper et al. (1990) that were taken from within an anticyclonic ring in the eastern Gulf. Although these plots are smoothed, some of the smaller scale vertical structures have been left in the plot in order to indicate that features of 50 to 200 m vertical dimension are significantly present. Note that the deeper currents below 1000 m are flowing in much different directions (~180°) relative to those at the surface. Direction changes below 800-1000 m associated with some type of counter-flowing structure are not unusual for the few measurements of the vertical profiles of horizontal currents in the LC and in LCR's that are available using AXCP's and XCP's (with the A indicating Airborne deployment). This is a characteristic of all such plots which are in Loop Current Rings or in the Loop Current on page 2379 in Cooper et al. (1990). The strongest currents occur in the uppermost 300 m depth range in Figure 1-14. In Figure 1-14, maximum (near surface) currents are ~100 cm/s. In the 800-1500 m depth range, speeds are ~5-15 cm/s, andthis region is also where directions can change rather abruptly by nearly 180°. Although in Figure 1-14 the maximum speeds in the LCR are only about 100 cm/s, in the strongest part of the Loop Current, near surface speeds of 150 cm/s and somewhat larger were found (Figure 2-20), also adapted from a figure by Cooper et al. (1990). In Chapter 2 (Figures 2-70 and 2-71), a much more energetic upper layer current section through a LCR centered at about 90°W is presented [based on data acquisition from an acoustic current meter by Forristall et al. (1992)]. One might wonder if the tendency of vertical profiles of horizontal currents in the easternmost Gulf tend to change sign in the vicinity of 800 - 1000 m depth is perhaps linked to the location of the sill depth of the Florida Straits in this depth range. In any event, the adjustment process of the current system flowing from the Gulf into the southern Straits of Florida is at least interesting. This topic is considered again in Chapter 2, in the vicinity of Figures 2-4 through 2-8. At that point, relationships are examined between property distributions in the Yucatan and Loop Currents with respect to those in the flow exiting the Gulf through the Florida Straits, where the effective sill depth is 700-800 m, and into the open North Atlantic Subtropical Gyre.

Figure 1-14: Current speeds (in red) and directions (blue line) as a function of depth from a site within an LCR in the eastern Gulf, adapted from Cooper et al. (1990).

END OF SECTION 1, OF CHAPTER 1, LAST UPDATED 17 DECEMBER 2003.