APPENDIX A: A LITERATURE REVIEW
PRIMARILY DEEP WATER
SECTION 1

Appendix A contains a more or less sequential discussion of the publication base for the low-frequency, large-scale circulation of the Gulf of Mexico from 1885 to the present, and includes references that could be useful for comparative study. Appendix A is designed to be a complement to the more topical parts of this review (Chapters 1-4 and Appendices C and D), as well as an extension of Appendix B, the Bibliography. Although publications are normally considered in approximate order of year of publication in Appendix A, there are several exceptions to this rule involved with combinations of papers on similar topics. Appendix A was partly motivated by earlier efforts in this vein by Elliot (1979) and Vázquez (1975), and is how I have become familiar with the circulation in the Gulf of Mexico. Low frequency is usually taken to mean periods of days and longer, to exclude tidal and inertial periods, and is sometimes referred to in the shelf and estuarine circulation context as the sub-tidal range. In Volume I, time scales involving monthly means and longer along with quasi-stationary flow patterns are the priority, order days time scales are considered in some detail in Volume II of this review. Large-scale implies circulation features with horizontal dimensions of about 50-100 km and larger, except in special cases where smaller scale processes play a noticeable role in the larger scale picture. In Appendix A, most but not necessarily all references, either scanned or read and listed in Appendix B, are the subject of a sentence or two, sometimes more. Additional material on a particular reference or a group of publications may be included, sometimes depending inversely on coverage in the topical Chapters and Appendices in this review. A few publications on coastal circulations, in the context of Chapter 3 of this review, and as a lead-in to Volume II, are also mentioned in Appendix A. A more complete presentation of the coastal circulation publication base for the Gulf of Mexico (GOM) is contained in Volume II of this review. One special feature of Appendix A is the discussion of a variety of publications not explicitly on the Gulf of Mexico, which are however likely to be useful from the point of view of comparative study or general perspective. Chapter 1 in *The Gulf Stream* (Stommel, 1965; please also see Stommel, 1957) contains a history of the early exploration of the currents along the western boundary of the North Atlantic Ocean. The Loop Current in the Gulf of Mexico is a component of the Western Boundary Current (WBC) System in the North Atlantic Ocean and is considered accordingly. The publications noted above by Hank Stommel have played a major role in the study of the WBC System in the North Atlantic Ocean, of which the Loop Current in the Gulf of Mexico is one component. Chapters and appendices in this review have been split into sections for ease in downloading, and each of these sections will be described briefly at their start, in analogy to the following short paragraph.

Organizational comments on Appendix A are contained in this paragraph: Section 1 of Appendix A (A.1) contains notes connected with publications prior to 1985, starting in 1885. Section 2 of Appendix A contains comments on publications from 1986 to the present. Just before a Brief Appendix Summary at the end of Appendix A.2, there is a short section involving references related to the current state of the art in eddy-resolving numerical ocean modelling on large scales in general, as discussed in Appendix C. Chapter A.1 was last updated on 22 February 2003 and there are about 23 pages and eight figure numbers involved (Figures A-1 through A-8). Page and figure numbering in this review is by entire Appendices, not Appendix Sections. The nomenclature used in Appendix A is discussed in other Chapters and Appendices in this review.

Pillsbury (1885, 1886, 1887, 1889, 1890) described a remarkable set of early measurements of currents in the Gulf Stream Regime and its "source regions". These included data that were used by Gordon (1967) in a pioneering study of the general Circulation in the Caribbean Sea to provide a set of current profiles at five depths across the Yucatan Current. These profiles are presented in Chapter 4 and discussed there as well as throughout this review. The earliest article that I've read that focuses on the circulation in the Gulf of Mexico is by Sweitzer (1898), who cited several earlier investigations of the Gulf Stream, including a report by Pillsbury. The Gulf Stream is called the Loop Current when flowing through the Gulf of Mexico, and this current pattern was to some extent known by Sweitzer, who proposed a "new" perspective for the general circulation of the Gulf of Mexico (his Figure 2; please see Figure A-1 here for an adaptation). According to Sweitzer (1898), the Yucatan Current makes a right hand turn directly from the Yucatan Channel into the Straits of Florida along the coast of Cuba, and in the western Gulf there is a wind-driven flow up the coast from the Campeche Banks to about Galveston, then approximately circumventing the rest of the Gulf of Mexico. Based on Sweitzer (1898), there is in Figure A-1 also a major cyclonic gyre just below the upper Gulf Coast, centered roughly a couple of hundred kilometers offshore of the Mississippi Delta. Sweitzer (1898) noted that this gyre was carrying discharge from the Mississippi River westward along the Louisiana Coast. He suggested that the area of convergence of the currents associated with the confluence of the western reaches of his cyclone and the northward flow along the Texas Coast involved "a considerable agitation" of the waters covering about 100 square miles, at a location about 40 miles south and 20 miles east of Aransas Pass, and noted the accumulation of a lot of debris on the coast nearby. As an aside, the Coastal Bend Area south of Port Aransas in South Texas is at this time a well known convergence zone for debris, as well as sand (Lohse, 1952, 1955).

Figure A-1: A schematic adaptation of an illustrative circulation pattern for the Gulf of Mexico, based on Sweitzer (1898).

Figure A-2: A colorized schematic adaptation of a map of the general circulation of the Gulf of Mexico, according to Haupt (1898).

Sweitzer's (1898) actual main interest was in the littoral transport of sand as related to jetty design and construction, and he was an advocate of from the south being the dominant direction of sand transport along the Texas Coast and specifically at Aransas Pass. The discussion and correspondence following the presentation by Sweitzer (1898) at a meeting of the Civil Engineering Society, which was published along with Sweitzer's paper, is incredibly interesting. Haupt (1898) delivered an excellent general critique of Sweitzer's presentation, and he proposed an alternate pattern for the circulation in the Gulf of Mexico (his Figure 3, here presented in somewhat modified form as Figure A-2). Although the dynamical thinking behind this proposal appears to be out of context, Haupt's (1898) scheme (Figure A-2) is significantly closer to the modern view than Sweitzer's. Haupt's (1898) view of the general circulation in the Gulf (Figure A-2), suggested a more extended Loop Current configuration than did Switzer's, and the cyclone-anticyclone pair in Figure A-2 for the western Gulf, although out of balance in terms of size and exact position, is remarkable, perhaps surprisingly close to today's view in very general qualitative terms.In Figure A-2 and other figures in this review, anticyclonic flow features are shown in red and cyclonic features in blue. The smaller light blue and red lines are used to possibly reflect Haupt's (1898) idea of interacting or "uniting" patterns of flow. Haupt (1898) also pointed out that whereas littoral sand transport in the vicinity of Aransas Pass did occur from the south at certain times of year (summer), the dominant sand transport was from the north in the non-summer months (this is the prevailing view today), the opposite direction to that suggested by Sweitzer (1898). So although very stimulating, Sweitzer (1898) was basically incorrect in many of his speculations (but not entirely so).

Figure A-3: An isotherm map (in °C) at 200 m depth, based on data presented by Parr (1935, his Figure 11).

Parr (1935) is an account of data from early hydrographic survey cruises in the GOM, and included a section across the lower or southern Straits of Florida from the Dry Tortugas to Havana. Although his observations were sparse by today's standards and not of notably high quality, Parr's (1935) database contains several features of the hydrography and circulation of the Gulf that are consistent with the modern view. Ichiye (1962) noted that unprotected thermometers were not used for depth determinations by Parr (1935). Elliot (1979) pointed out that the unprotected thermometers from the 1932 expedition by the *R. V. Mabel Taylor* were broken immediately before the cruise. Some of the Parr (1935) data were presented in Chapter 1 (Figure 1-3), in the context of a figure originally developed by Ichiye (1962). Figure 1-3 contains a Loop Current with northern boundary up against the continental slope/shelf regime associated with Mississippi Delta and possibly in the process of shedding a warm core eddy. This was the first deep penetration of the Loop Current on record, based on in-situ data, insofar as I know. However, the Loop Current in Figure A-2 is also shown to schematically penetrate quite far north into the Gulf of Mexico (Haupt, 1898). Parr's distributions of temperature and salinity at 200 m depth in the GOM (1935, his Figures 11 and 12) indicate a separated warm core eddy in the western Gulf near 93-94°W and 23°N (Figures A-3 and A-4), with a subtropical underwater signature (comparatively high salinities) indicative of origin in the Caribbean Sea and upstream in the subtropical and tropical North Atlantic Ocean. Figures A-3 and A-4 also contain an anticyclone near the continental slope over the continental rise in the northwestern Gulf, but with a fresh water signature. This was the initial data-based observation of distinct eddies in the western Gulf, uniquely recognized as such by Elliot (1979). Parr (1935) correctly attributed the comparatively low near-surface salinity that he observed on the LATEX Shelf as being associated with discharge from the Mississippi River. Parr (1935) also compared his section across the Florida Current at the longitude of Havana, Cuba with data from other sources, and in other publications in the nineteen - thirties explored the hydrography of the Caribbean (Parr, 1937a) and the Straits of Florida off Miami, Florida (Parr, 1937b). It was many years before additional hydrographic surveys of the Gulf-wide circulation were completed, with an article published on these results by Austin (1955).

Figure A-4: An isohaline map (in psu) at 200 m depth, based on data presented by Parr (1935, his Figure 12).

In the early days of scientific study of the general or large-scale circulation of the North Atlantic Ocean, Wust (1935, please see the English translation edited by Emery, 1978) published a remarkable view of the deep and abyssal flow there (based on comparatively early hydrographic data acquisition), many elements of which have prevailed to this day. Wust (1935) used, for example, the water mass identifiers Upper, Middle, and Lower North Atlantic Deep Water, and in his Figure 48 (Wust, 1935, p.111) set out a schematic diagram of the meridional overturning associated with deep and abyssal flows (he used the name stratosphere) in the North Atlantic Ocean. This picture is considered in some detail in Appendix D of this review, where it is pointed out that the upper ocean MOC return flow in the Atlantic Ocean and some of the characteristics of the general circulation in the Caribbean Sea and the Gulf of Mexico are linked in a perhaps unanticipated way. Wust (1935) also noted that the most pronounced deep and abyssal water mass circulations associated with his view of meridional overturning circulation (MOC) were typically concentrated on the western side of the Atlantic Ocean (for example, please see his map of the spreading of Middle North Atlantic Deep Water; Wust, 1935, Insert XXI), probably the first observational suggestion of the existence of Deep Western Boundary Currents (DWBC). Some of the activities nearly concurrent with the investigations by Parr (1935; 1937a,b) in the GOM and the Caribbean Sea, but in the vicinity of the mid-latitude Gulf Stream are of interest. Iselin (1936) observed a cold core Gulf Stream Ring [for the first time (in 1932) possibly, please see his figures 10 and 11]. Iselin (1940) discussed a cold core Gulf Stream Ring that was observed in 1937. Somewhat before or concurrent with the next wave of exploration in the GOM, Iselin and Fuglister (1948) described early observations of Gulf Stream Rings. Pillsbury's (1890) results in the vicinity of the Passages into the Caribbean were used by Model (1950) to estimate transports there. Haurwitz and Panofsky (1951) suggested that meanders and eddies in the mid-latitude (north of Cape Hatteras) Gulf Stream System could be due to instability processes, a topic later pursued by Ichiye (1962) in the GOM. Fuglister (1951) developed a picture of annual surface current fluctuations at various locations in the Gulf Stream System, based on data in an atlas published by the US Navy. These results were later used in comparison with the seasonal fluctuations in the Yucatan Current by Cochrane (1965). Fuglister and Worthington (1951) documented the separation of a meander-ring for the Gulf Stream during Operation Cabot.

The next publication containing information relevant to the Gulf circulation, but primarily about the wind field there, was in 1953. Franceschini (1953) presented maps of the monthly averaged wind-stress in the GOM, and related these distributions to surface currents (as indicated by pilot charts), and temperatures as possible. These maps were based on tabulations of winds in two degree squares that used ship observations for the period 1855-1950, and the gross features of the monthly mean maps are similar to some later collections (for example; Elliot, 1979). According to Franceschini (1953), there were qualitative indications that the currents near the sea surface in much of the western Gulf were at least partially wind driven, for example when comparing the wind field in the summer to the pilot chart for July. He also commented on cyclonic winds in the winter in Campeche Bay and the cyclonic current pattern there in the Pilot Chart for January. He noted that when the wind stress was parallel to the shoreline, the coastal surface currents tended to be in the direction of the stress, and mentioned the possibility of coastal upwelling in the westernmost Gulf during the summer. These suggestions are compatible with the prevailing ideas at this time. He also made a point of the probable downcoast drift in the non-summer months. So he had a fairly clear, but not well-developed picture of the zero order properties and seasonality of the coastal circulation in the northwestern Gulf. Toward the end of his report, Franceschini (1953) emphasized the possibility of summer upwelling along the Texas Coast (with the “necessary southerly” wind component moving northward from May to August), and related this possibility to a map of the distribution of sea surface temperature in July. According to Leipper (1954a, p.121), little was known at that time about the currents in the GOM, with pilot charts of surface currents being the chief source of information. Leipper (1954b) is a brief review of the Gulf’s Marine Meteorology. Leipper (1954b, his figure 18) contains a highly smoothed map of sea level pressure over the Gulf in July, a broad brush indicator of anti-cyclonic summer wind circulation on Gulf wide scale. Marmer (1954) published a pioneering paper that examined coastal water levels on a variety of time scales, including especially monthly mean sea level (MMSL) around the Gulf Coast, please also see Marmer (1952). Coastal sea level is an important element in Gulf-shelf-estuarine interaction, and its properties will be examined in that context in Volume II of this review.

Austin (1955) described the large scale circulation of the GOM based on six hydrographic survey cruises that were executed in the time frame 1951-1954. Three of these cruises occupied stations primarily in the eastern Gulf, in the Loop Current and its vicinity. Anticyclonic eddies were observed in various stages of connection to, and location in, the Loop Current in the eastern Gulf, but not distinctly separated and drifting westward as isolated features, although there was considerable evidence of neck formation (the initial stages of pinch off of current rings). Of the five maps presented by Austin (1955, his figures 2-6), four clearly were suggestive of the early stages of formation of Loop Current Rings (LCR's, as discussed throughout this review). The data from three cruises on the R/V Alaska between 22 April and 21 August 1951 were combined to yield a map of surface currents based on dynamic heights covering the Gulf of Mexico, for the first time according to Austin (1955). This map (Please see Figures 2-1 and A-7, and associated discussion) contains several flow features with a variety of horizontal scales, including indications of both cyclones and anticyclones in the central and western Gulf. Chew (1955) described the hydrography and circulation on the west Florida shelf and continental slope. He identified a cyclonic eddy on the shelf off the coast of Tampa and another just north of the northernmost extension of the Loop Current off the coasts of Mississippi and the Florida Panhandle. Von Arx et al. (1954, 1955) described the existence of shingles or frontal eddies (also noted by Fuglister, 1951; perhaps first observed by Spilhaus, 1940, note for example his figure 21 on the inshore edge of the Gulf Stream), please also see Webster (1961). Frontal eddies, which are very important to the circulation in the GOM, are dramatically understudied there, especially with respect to the situation off the southeast coast of the United States, as noted throughout this review.

Collier et al. (1958) is a data report for the cruises in the early 1950's whose results relative to circulation were described by Austin (1955). In this data report Collier et al. (1958) also show some interesting salinity distributions near the mouth and just east of the Mississippi River. Wenneckens (1959) examined the hydrography of the Straits of Florida and its relation to similar characteristics in the GOM. McLellan (1960) described and discussed the hydrographic data acquired on 3 cruises of the R. V. Hidalgo in 1958 and 1959. One of these cruises crossed the Straits of Yucatan with 5 stations, and indicated strong northward flow on the west side of the straits, with a slight counter-current in the eastern side of the channel, near the coast of Cuba. The T-S plots in the Yucatan Straits for the Hidalgo cruise were shown to be approximately similar to previous sections (Atlantis 1935, Crawford 1958) . McLellan (1960) suggested that his results for cruise 58-H-4 (his Figure 27) implied upwelling along the continental slope and outer shelf in the northwestern Gulf, and also a more permanent circulation (strong eastward flow) over the slope. In addition, upwelling was observed across Campeche

Bank (Figure 8 by McLellan, 1960). Cochrane (1961) summarized the results of two cruises to the Yucatan Current Regime in 1960 and 1961. Much of the discussion was on westward intensification in this region (Chapters 2, 4, and Appendix D), which was found to decrease with depth (as in the rest of the Gulf Stream System). The observation was made that the maximum geostrophic speed was closer to the middle of the Yucatan current at 300 m depth that for the surface currents. Westward intensification in the density field was observed as far south as 18°N. Upwelling just north of the inshore or left hand side of the Yucatan Straits was a topic of interest, as were eddies along the eastern side of the Yucatan Current. Temperature and salinity profiles and the basic data acquired during the 1957-58 IGY (International Geophysical Year) were published in an atlas by Fuglister (1960), referred to by Stommel (1965, p.188) as an important work and a handsome colored atlas to which anyone interested in the Gulf Stream would frequently want to make reference. This atlas was the most basic observational introduction to the large-scale circulation in the Atlantic Ocean for my generation of students of descriptive oceanography.

Ichiye (1962) is historically a notably significant article on the circulation in the Gulf, both in terms of the discussion of various data sets [mainly those acquired and described by Parr (1935) and Austin (1955)] as well as in interpretation of meandering and stability of the Yucatan Current and ring formation (as associated with instability processes), along with some suggestions about the seasonally-wind-forced circulation. Ichiye (1962) suggested, for example, on the basis of the observed distribution of the depths in the Gulf of the sigma-t surfaces 27.2 and 27.5 kg m^{-3}, that water masses had separated from the Loop Current and formed anticyclonic gyres. He found a comparatively large anticyclonic vortex located in his sigma-t =27.5 kg m^{-3} depth map near 24°N in the western Gulf and suggested that this gyre might originate from the east. This is today known to be a canonical location for a warm core eddy that has separated from the Loop current in the eastern Gulf and propagated into the western Gulf (Chapter 2). Ichiye (1962, please also see Ichiye, 1956) in general applied the experience that he had developed in studying the Kuroshio Current System to the Loop Current in the GOM. He was also familiar with a variety of investigations in the mid-latitude North Atlantic as indicated by his bibliography. In the 1960's, studies of eddies and meanders in the mid-latitude Gulf Stream had been under way for several years (Stommel, 1965). In addition to previously mentioned activities, Fuglister (1963), for example, described the results of a multi-ship survey of the Gulf Stream east of Cape Hatteras that was executed in 1960. Very large meanders (called "socks") were observed and identified as being in the process of breaking off to form a separate eddy. Ichiye (1962) is discussed in more detail in Chapters 1 and 2 in this review.

Duxbury (1962) put together a composite view of various dynamic height distributions in the Gulf, based on the hydrographic data that had been acquired in the 1950's. His dynamic height distribution relative to 1000 db contains many features that resemble the modern picture. Cochrane (1962) described both onshore and offshore locations (meanders) of the axis of the Yucatan current as observed during several cruises, and considered the seasonal fluctuations of the currents in the Yucatan Channel. Regions of anomalously cold water over the Yucatan Shelf were discussed in terms of upwelling onto the shelf, both wind and current induced. Cochrane (1963) described the structure of the Yucatan Current at the sea surface in detail, utilizing various data sources. McLellan and Nowlin (1963) described a variety of water properties in the deep Gulf (still an under-sampled regime), based on 52 hydrographic stations taken in 1962. Wust (1963, 1964) contain a broad spectrum of information on the deep circulation in the Caribbean Sea and its approaches. Wust (1963; his Figure 2) shows what he called Subantartic Intermediate water entering the north Atlantic as a western boundary Current and flowing into the Caribbean through its southern passages. Wust (1964) is a wide-ranging study of the general circulation of the Caribbean Sea and environs, please see Appendix D.3 for more discussion. Wust (1964) described, for example, the distribution of the upper ocean salinity maximum characteristic of Subtropical Underwater, which has been widely used in the Gulf as an indicator of the presence of water coming from the Caribbean. Chew (1964) was an important contribution to our perception of the processes associated with the distribution of monthly mean sea level, both in general and explicitly in the northern Gulf. Results from a series of surface drifter studies on the continental shelf in the western and northwestern Gulf of Mexico, as well as one current meter record, were published by Kimsey and Temple (1963, 1964). Maps of drifter results were presented for winter, fall and summer intervals, which again indicated a pattern involving mostly upcoast currents in the summer, downcoast otherwise. The results presented by Kimsey and Temple were the first explicitly direct measurements made (as far as I know) to determine currents over a fairly large area on the continental shelf in the western Gulf of Mexico and delineated the westward currents along the coast from the Mississippi Delta as well as the Texas Coast, which had previously been studied by Sweitzer (1898), Haupt (1898), Bullard (1942), and Lohse (1952, 1955).

The measurements by Kimsey and Temple (1963, 1964) extended from the mouth of the Mississippi River around and down the Texas coast to the mouth of the Rio Grande River, approximately, and were distributed from 60 stations laid out over the continental shelf out to the 100 fathom depth contour. Kimsey and Temple presented a map for February 1962 that exhibited a general westerly, alongshore drift on the LATEX shelf, along with currents flowing southwestward down the coast from say, Galveston to Brownsville, with current magnitudes between .4 to .7 knots. However, up the coast flow between Brownsville and St Josephs Island was observed in the immediate vicinity of the coast. The map for the last 2 weeks of July 1962 presented by Kimsey and Temple (1963, 1964) contained a mostly northeastward flow off the coastal bend and an eastward flow on the eastern part of the LATEX Shelf. The flow off South Texas was very well defined (the best I've seen for the South Texas Shelf, drifter recovery was outstanding in this instance), and possibly indicative of coastal upwelling. A similar map for September 1962 (Kimsey and Temple, 1964) indicated the flow had turned back to down the coast. The database acquired and/or discussed by Parr (1935) and Austin (1955) was sparse at best, and not of particularly high accuracy and precision. Ichiye's (1962) discussion and analysis of the general circulation of the GOM was inspired to say the least, but it was somewhat speculative [although rings had been clearly observed in other strong current regimes, please see for example Olson (1991) for some historical context]. So there was a need for near-synoptic high-quality hydrographic data at the closest possible station spacing in order to proceed with confidence in the description of the general circulation of the GOM. According to Elliot (1979), this approach was implemented in the 1960's and 1970's, please also see Nowlin (1972). McLellan and Nowlin (1963) used hydrographic data collected on the R. V. Hidalgo in February-March 1962 to study the flow patterns and hydrographic characteristics in deep water (depths of 1500 m and larger) in the Gulf of Mexico. Horizontal variations in potential temperature and salinity did not exhibit any notable pattern, and vertical gradients were small below 2000 m, consistent with an isolated basin having a sill depth of roughly 1500-2000 m depth. Bryan (1963) and Bryan and Cox (1967) are often quoted pioneering papers in the formulation and application of numerical models to the study of the ocean circulation.

Jones et al. (1965) carried out a year long (nominal) hydrographic survey for the inner shelf off Port Aransas, Texas and found comparatively cool water inshore in the summer months sampled, with sigma-t contours creeping in along the bottom toward the coast from the outer shelf in May and June, and continuing in July. Cochrane (1965) described and discussed seasonal fluctuations in the surface layer of the Yucatan Current. He used monthly pilot charts on the western side of the Yucatan Channel to come up with a typical curve of "the annual march" of the surface currents in the Yucatan Current. These results were examined in the context of a variety of observations including a comparison with Fuglister's (1951) results for the Florida Current in the vicinity of Miami. The shape of the curve for the Florida current and the Yucatan current is similar and both 12 and 6 month contributions are clearly present. For the Florida Straits, Fuglister (1951) estimated the total yearly variability to be 16% of the mean, partitioned as 11% due to 12 month fluctuations and 5% associated with 6 monthly variability. Cochrane (1966) described a GEK survey of the Yucatan Current and its northward penetration into the GOM in September 1965 that (according to Cochrane) yielded a totally different current/hydrographic pattern than found on any previous cruise. The Yucatan current was way offshore of Campeche Bank and flowing toward about 030°T more or less directly into the Straits of Florida without forming much of a loop. Just to the north there was an indication of a detached eddy. This was probably an early observation of the separation of a warm core ring having recently occurred. Cochrane (1967) gave a brief discussion on upwelling off the northeast coast of the Yucatan Peninsula.

Armstrong and Grady (1967) described the results of a late winter (20 February-1 April, 1967) cruise on the R. V. *Geronimo*. Leipper (1967) wrote a technical report on the circulation in the GOM, a precursor to a paper published in 1970. Gordon (1967) described the circulation in the Caribbean Sea, including a presentation of the distribution of direct measurements of currents in the upper 250 m depth range (nominal) at the Yucatan Straits. Holland (1967) was an early-on study of the effect of bottom topography on the large-scale wind-driven ocean circulation using a numerical model. The results of a Gulf-wide hydrographic survey from mid-February to the end of March 1962 (Cruise 62-H-3, RV Hidalgo) were described by Nowlin and McLellan (1967). A major anticyclonic feature in the central western Gulf penetrated zonally across most of the Gulf. Results from this cruise, several of which are used throughout this review and especially in Chapter 2, were subsequently summarized and reviewed by Nowlin (1972), as discussed further later in this Appendix. Hubertz (1967) examined the LC using data acquired on a cruise in June 1966 (Cruise 66-A-8), where 56 hydrographic stations were made with a station separation of 40 nautical miles. Both Nansen Bottle and STD casts were obtained and compared. The surface expression of the LC (Hubertz, 1967, his figure 1) was in a moderately extended, fairly simple configuration. The LC extended as far north as 27.5°N , with a small loop like feature at the northern tip of the main LC. Hubertz (1967) found a closed eddy transporting about 15 Sv within a Loop Current transporting about 30 Sv, a total of roughly 45 Sv all referenced to 1350 db. Surface speeds were 2 to 3 knots and were about 1 knot in the depth interval 150-200m, in the same range as Pillsbury's (1887) data as presented by Gordon (1967), please also see Figure 2-4. Figure A-5 is a deep flow pattern adapted from Figure 5b by Hubertz (1967), presented here since there are not many such pictures available for the deep flow in the LC Regime. The pattern of deep flow in the vicinity of the Loop Current in Figure A-5, as indicated by the contours of dynamic height for the pressure interval 900/1350 db, is a bit larger in approximate size and magnitude relative to the pattern in Figure 2-17, the latter based on 1000/1500 db dynamic heights .

Figure A-5: Deep flow in the vicinity of the Loop Current according to Hubertz (1967), based on dynamic heights (in dynamic cm) at 900 db relative to 1350 db.

On a cruise in 1967, Nowlin et al. (1968) clearly observed for the first time a detached Loop Current Ring, or warm-core eddy, please see Chapter 2, Figure 2-14. Cochrane (1968) described the results of a GEK survey of the surface currents in the northwestern Caribbean, in the Yucatan Channel, and in the Loop Current Regime up to about 26°N (his Figure 1). Schmitz and Richardson (1968) contained the initial results of applying dropsonde techniques (Richardson and Schmitz, 1965) to the study of the transport of the Florida Current. Schmitz and Niiler (1969) studied eddy-mean flow interactions in the Florida Current off Miami, and their data at the sea surface were used in Figure 2-2. Richardson et al. (1969) published an extensive set of measurements on the structure and transport of the Florida Current from Cay Sal Bank to Cape Fear, North Carolina, please see the resume by Schmitz (1996a), and Appendix D.3. The portions of this data set from the Straits of Florida were the subject of a masters thesis by Clausner (1967), who also favorably compared these results with Pillsbury's (1890) database between Fowey Rocks and Gun Cay, B. W. I., as well as various hydrographic data, these topics are discussed further in Appendix D.3. Cochrane (1969a) summarized his previous observations of cool cyclonic domes of water at the eastern edge or corner of the Campeche shelf next to the Yucatan Current, mostly made in May. He also considered a couple of possible origins for this water and preferred an intrusion from the Yucatan Current. Cochrane (1969b) described hydrographic and GEK observations in the Yucatan Straits and in the Loop Current. Observations of 20°C isotherm depths and concurrent GEK data (Figure 2 in Cochrane, 1969b) obtained in1968 (Cruise 60-A-5, May 1968) demonstrated westward intensification of the currents in the western Cayman Sea and especially on the western side of the Yucatan Straits, along with a reasonably well-defined Loop Current configuration. Cochrane (1969b, Figure 1) used observations of the depth of the 20°C isotherm as well as some limited GEK data to clearly demonstrate the penetration of a cyclonic feature into the LC from the east (the southern segment of this cyclonic feature is just south of the Dry Tortugas), between 24°N and 26°N in May, 1979 (Cruise 69-A-7). This is another early example of necking down of the Loop Current, at a comparatively southerly latitude. However, the definitive discussion of this figure and associated observations was not published until Cochrane (1972). A discussion of the current patterns in the Gulf of Mexico by Leipper (1970) focused on the path and structure of the Loop Current based primarily on data acquired in the mid-1960's. Some of these results are discussed in Chapter 2. Worthington and Wright (1970), and Wright and Worthington (1970) are atlases for the Atlantic Ocean that are key resources.

Schmitz et al. (1970) observed strong, bottom intensified abyssal currents (near the bottom of the ocean) under the Gulf Stream over the continental rise near 70°W, perhaps a precursor for similar features as found over the continental rise in the northern Gulf of Mexico. Emilsson (1971) presented results from a hydrographic and GEK survey of the northern Caribbean that was carried out from 15 to 28 August, 1971. His results indicated a current regime in the survey area that switched from the zonal to the meridional direction up against the coast off the Yucatan Peninsula, with a strong counter current on the eastern side of the Yucatan channel. An eddy was found between Cuba and the western boundary current coalescence region. These features are reminiscent of the later studies of Schlitz (1973) and Molinari (1976). Whitaker (1971), in an impressive masters thesis, described the seasonal variations in the hydrography of the upper layers of the Gulf, and determined and discussed seasonal steric effects on monthly mean sea level (MMSL). Steric effects are due to expansion and contraction of water columns associated primarily with heating and cooling. Marmer (1954) had given the initial summary description of the characteristics of the "annual march" of MMSL around the GOM, and identified both twelve and six month time scales in these distributions, with characteristically a secondary spring maximum at sites in the northern or northwestern Gulf (the Galveston MMSL data is a good example) to go along with a more widely observed fall maximum. Whitaker (1971) could account for part (a late winter minimum and an early fall maximum) but not all of the Marmer (1954) results with respect to observed MMSL distributions. In particular, a summer minimum is not present in the steric MMSL, nor is a secondary spring maximum. The discussion of these issues by

Whitaker (1971) was very thoughtful and helpful. The Gulf-wide maps of the monthly-averaged depth of the 22°C isothermal surfaces developed by Whitaker (1971, his figures 3 through 14; pp. 14 - 25), were based on data acquired between 1940 and 1965. Insofar as I know, this study and these figures contain the first more or less complete picture of the annual march (please see Chapter 2, section 7) of the monthly mean upper-level Gulf-wide temperature signal. Hsueh and O'Brien (1971) considered the development of a shelf circulation involving upwelling induced by a current at the seaward edge of the shelf and perhaps farther offshore. Rinkel (1971) is an initial discussion of a multi-disciplinary program in the Loop Current Regime. During the first phase of this effort, two cyclonic frontal eddies were observed on the northern boundary of the Loop Current (in late April, 1970), and were found to penetrate to 700 m depth.

According to Elliot (1979, 1982), whereas Ichiye (1962) was the first to suggest the formation of large warm core eddies called in this review Loop Current Rings, Cochrane (1972, with 1969 data) was the first to distinctly observe the separation and westward propagation of an LCR , and estimate the translation speed [although, as noted above, Nowlin et al. (1968) had described a detached eddy found on a cruise in 1967]. Cochrane (1972) was an important publication, containing the initial discussion of a mechanism for the formation of Loop Current Rings that involved pinching off by one or more cyclonic features between Campeche Bank and the southwest Florida shelf. The original indication of a mechanism of this type was based on Figure 1 by Cochrane (1969b). Fuglister (1972) described cold core gulf Stream Rings in much detail. Leipper et al. (1972) discussed in detail an isolated eddy that was observed in 1965, and described to some extent earlier by Cochrane (1966) and Leipper (1970). This detached LCR (Leipper et al, 1972) was located close to the straits of Yucatan just north of the northeastern edge of the Campeche Escarpment. Holland and Hirschman (1972) extended previous numerical model results to include both baroclinicity and variable bottom topography.

Nowlin (1972) discussed most of what was known at the time of his publication concerning the general circulation of the Gulf of Mexico, with emphasis on winter conditions. Although, most of the hydrographic data base was considered, the benchmark or cornerstone cruise was executed during February-March 1962 from the R/V Hidalgo (Cruise 62-H-3), as described and discussed by McLellan and Nowlin (1963) and Nowlin and McLellan (1967). According to Nowlin (1972), Cruise 62-H-3 was more carefully planned than previous cruises, using modern methods of salinity and oxygen determination, and achieving nearly synoptic Gulf-wide coverage (station spacing about 2 degrees of longitude, but with closer spacing near the LC, the Yucatan Channel, the Florida Straits, and in the westernmost Gulf, please see Figure 1-1 by Nowlin, 1972). Nowlin (1972) emphasized the dominance of the Loop Current in the eastern Gulf, along with a prominent anticyclonic or clockwise cell in the western central Gulf (his Figure 29), please see Figure 2-16. The history of previous investigations into this "western anticyclone" were reviewed by Vázquez (1975), along with a discussion of cyclonic flow in the southwest corner of the Gulf near Campeche Bank (as discussed below). The review by Nowlin (1972) is used extensively in Chapter 2 of this review. The T-S curves above 17°C presented by Nowlin (1972, his Figure 1-4, his p.8) reflect comparatively fresh water entering the Gulf on the western side (Stations 11-13, Cruise 62-H-3) of his Yucatan Channel section and exiting through the northern side of his Florida Straits section (Stations 25-28, Cruise 62-H-3). The water in the uppermost layer entering the Gulf at the Straits of Yucatan and exiting through the southern Straits of Florida can also become less saline through winter convection in the northern Gulf (Wenneckens, 1959), as well as through the influence of the discharge through the Mississippi River System. Also in this temperature range, saltier water enters on the eastern side of the Yucatan Current (Stations 15-20, Cruise 62-H-3) and exits on the southern side of the Florida current section (Stations 11-13, Cruise 62-H-3) (Stations 20-24, Cruise 62-H-3). The kinds of property distributions discussed in the last few sentences were used by Schmitz and Richardson (1991) as one component of the basis for the idea that the transport of the Florida Current is part South Atlantic and part North Atlantic in origin, as discussed further in Appendix D.

Figure A-6: Dynamic topography (contours in dynamic cm) for the sea surface relative to the 1000 db surface, highs are red, lows blue. Based on data from a cruise on the Mabel Taylor (24 January to 27 April 1932). Dashed depth contours (smoothed) are shown for 200, 1000, and 3000 m.

Figure A-6 is an adaptation of a map published by Nowlin (1972) depicting the dynamic heights (0/1000 db) based on the data acquired on the Mabel Taylor cruises by Parr (1935). Nowlin (1972) noted the general resemblance between results from 62-H-3 (Nowlin and McLellan, 1967) in Figure A-6, in contrast to results published by Austin (1955), shown as Figure 3 by Nowlin (1972), Figure A-7 here. Figure A-6 is shown here as an aid interpreting the map (Figure 1-3), published by Ichiye (1962) and based on the Parr (1935) data, as well as Figures A-3 and A-4. Figure A-6 clearly exhibits a warm core anticyclonic eddy in the western Gulf (labeled WA in red), as well as a warm-core ring or anticyclone with center near 89°W and 26-27°N that is partially attached (reattached) to the Loop Current (labeled NDE, nearly detached eddy in red), both features also present in the Cruise 62-H-3 results. The northernmost anticyclone in the western Gulf that is shown earlier in Appendix A as Figures A-3 and A-4 [based on Parr's (1935) Figures 11 and 12] is not present (not shown) in Figure A-6 except as one data point. The cold cyclonic intrusion into the LC as contained in Figure 1-3 is also present (labeled CI in blue) in Figure A-6 near 27°N and 85°W, but appears less extensive than it does in Figure 1-3, which is based on the 200 m temperature distribution in the eastern Gulf. The dynamic height map by Austin (1955) that was presented by Nowlin (1972) and is shown in adapted form as Figure A-7 here, contains a fairly large and dense population of both cyclonic and anticyclonic eddies that is similar to many modern SSH maps, and resembles in some respects Figure 5 by Elliot (1982). It is worthy of note that the dynamic heights in Figure A-7 look similar in pattern in the eastern Gulf to the distribution of temperatures at 200 m depth in Figure 2-1 [adapted from Ichiye (1962)], but in the central Gulf these patterns are notably different. The dumbell shaped anticyclone in the western Gulf along 92°W in Figure A-7, with cyclones possibly pinching it down (seen for the first time in the western central Gulf in this figure), is similar to some of the SSH maps from about 10-15 years as later published by Biggs et al. (1996). The location of the cyclonic eddies in the eastern Gulf is reminiscent of many SSH and SST maps published much later, for example by Fratantoni (1998), including the near pinch-off of a comparatively small anticyclone in the vicinity of Desoto Canyon. The pair of cyclones in the Northwestern Gulf in Figure A-7 is suggestive of more modern results by Niiler (1999) and Hamilton (1992, 1998, 2002).

Figure A-7: Dynamic topography (contours in dynamic cm) for the sea surface relative to the 1000 db surface, highs (H) are red, lows (L) blue. Based on data from various cruises between 22 April – 21 August, 1951. Dashed depth contours (smoothed) are shown for 200, 1000, and 3000 m.

Nowlin and Hubertz (1972) described and discussed the results of two summer hydrographic surveys in the eastern GOM. On one of these summer cruises (1967), a detached eddy was observed for the first time (Nowlin et al., 1968), please see Chapter 2. Reid (1972) and Molinari and Cochrane (1972) studied the dynamics of the Loop Current and the Yucatan Current respectively. Cochrane (1962, 1963, 1966) had previously noted that while in comparatively shallow water (depths 500 m or so and smaller under the current core), that the path of the core of the Yucatan Current tended to follow an isobath and/or a strong bottom slope. Pasgausky and Reid (1972) and Wert and Reid (1972) were early on attempts at using numerical models to study the Gulf circulation. Carruthers (1972) described the TS characteristics of intermediate water masses in the Gulf, based primarily on data from cruise 62-H-3. Schlitz (1973) described the vertical structure and transport of the Yucatan Current in some detail, and his results are discussed throughout this review, starting in Chapter 2. Ichiye et al. (1973) examined various features of both shelf and deep circulations in the eastern GOM, with quite a bit of attention also devoted to estuarine characteristics in that area. Several other topics were also reviewed and summarized. In Chapter 4 of Ichiye et al. (1973), the Loop Current and the formation of LCR's were described and discussed. In general, the sections of Ichiye et al. (1973) report that covered the large scale circulation and hydrography were focused on trying to fit the data into a seasonal cycle, although exceptions to this were noted. Detached cyclones were present in a schematic figure by Ichiye et al. (1973, their Figure 4-1), not later mentioned in their Chapter 4, but extensively discussed in Chapter 5. Ichiye et al. (1973) also attempted to identify a seasonal relation or connection between the structure of the LC and the detached cyclones in their Chapter 5, based primarily on ship drift data. In their Chapter 6, on hydrography, Ichiye et al. (1973) do detect a possible cyclonic cold core eddy at 100 m depth, with diameter 100-150 km, near the continental slope and shelf break (perhaps trapped there) in the vicinity of 26°N and 85°W, based on data from Cruise 62-H-3. Ichiye et al. (1973) mentioned that the flow and its properties over the slope and at the shelf break off the west Florida Shelf tended to be parallel to bottom depth contours, seldom crossing over the shelf. Robinson (1973) is an atlas of monthly mean properties of the upper layer thermal properties in the GOM and the Caribbean Sea. In this atlas, thermal features are presented in the form of monthly mean temperatures at selected depths from the surface to 150 m. The western anticyclonic feature or western anticyclone is prominent in this data set also, especially at depths of 150 m. Nowlin and Parker (1974) described thermal fronts on the Latex Shelf that were associated with the passage of atmospheric fronts, apparently a first according to Oey (1986). The temperature field on the shelf cooled by about 5°C at the sea surface (Figure 4 in Nowlin and Parker, 1974) near the coast after the frontal passage, and the isotherms became more vertical, out to almost the shelf break (the upper 50 m or so). Maul et al. (1974) identified cyclonic eddies in the eastern Gulf from satellite data. This was possibly the earliest post-Cochrane (1972) effort to explicitly study cyclones observationally. Chew (1974) examined the structure of the Loop Current System using a dynamically based analysis of surface drifter and hydrographic data (his figure 1) acquired in the vicinity of October, 1970.

Figure A-8: Contours (in red) of the depth of the 22°C isothermal surface in the eastern Gulf of Mexico during July 1969, based on data from Cruise 69-A-10. Dashed line depth contours as indicated.

Schroeder et al. (1974) observed and described another detached ring from the Loop Current, based on hydrographic data obtained on a cruise (69-A-10) during the summer (1-31 July) of 1969. Figure A-8 is a modified form of Figure 8 by Schroeder et al. (1974), using selected contours of the depth of the 22°C isotherm, on a different base map. Cyclones are not present on Figure A-8, as they are in Figures 2-13, 2-14, 2-15, and 2-16, probably due to the sampling pattern used. Schroeder et al. (1974) also observed an anticyclone in canonical position (please see Chapter 2) in the westernmost Gulf. Lee (1975) studied shingles or frontal eddies or spin-off eddies on the inshore boundary of the Florida Current, based on current meter data from the narrow coastal domain inside the Florida Current off Boca Raton, Florida. The basic result was that a comparatively large number of cyclonic current reversals that were neither tide nor wind induced were observed. Lee (1975) interpreted these results as indicative of cyclonic spin-off eddies on the inshore edge of the Florida Current, in analogy to such features previously observed by Von Arx et al. (1954, 1955), and called shingles. Molinari and Kirwan (1975) discussed the kinematical and dynamical characteristics of drifters deployed in the northern Cayman Sea and found that their trajectories approximately conserved potential vorticity. According to Vázquez (1975), relatively few oceanographic cruises had been made in the southwest GOM since Parr (1935). He helped obtain and then used the data acquired on cruises from October 1970 to November 1971 by the Mexican Government using the R/V *Uribe.* Vázquez (1975) confirmed the dominance of the western anticyclone, which he named the Mexican Anticyclone. The existence of cyclonic flow features in the southwest corner of the Gulf, south of the semi-permanent anticyclone typically located near 23°N there, were also described by Vázquez (1975). Such features were present in most of the cruises. A pronounced cyclone was found in the southwest corner of the Gulf centered near 21°N, 94°W during a cruise made in November 1971 (Figure 18 in Vasquez,1975). Vázquez (1975) pointed out that the pilot charts show a closed cyclone in the Bay of Campeche from roughly November through April, but that it does not fill the bay the way the pilot charts indicate. Vukovich and Crissman (1975) was a comparatively early on study of the western boundary of the Gulf Stream using satellite data. Angelovic (1975) called attention to the Brownsville area as potentially upwelling favorable. Holland and Lin (1975 a,b) were the first to demonstrate that the Gulf Stream recirculations at mid-latitude were probably eddy driven, please also see Holland (1978). These and other modelling papers mentioned in this appendix (especially at the end of Appendix A.2) are also discussed in Appendix C, mainly presented in this review as an aid to the reader with respect to existing eddy-resolving modelling activities.

Sturges and Blaha (1976) suggested that the anticyclonic flow feature in the western Gulf as described by Nowlin and McLellan (1967) could be driven by the curl of the wind stress (the latter information as presented by Hellerman, 1967), and associated with a western boundary current in some analogy to the subtropical North Atlantic Ocean. The wind-stress curl used for the Gulf had a value of -7.5×10^{-9} dynes cm^{-3} (units hereafter understood) in the winter (December through February) and -3.9 in the summer (June through August), more or less vanishing in the spring and fall. Sturges and Blaha (1976) estimated that the western Gulf could exhibit a western boundary current like transport of approximately 6 Sv in the winter season. Molinari (1976) described the formation region of the Yucatan Current in the northern and western Caribbean (please see Chapter 2, in the vicinity of Figure 2-3). The current patterns in the northwestern Caribbean were mapped, over three time intervals of a week or two each, during cruises in the summer of 1971. The more or less westward flowing Caribbean Current was observed to coalesce and flow northward against the coasts of British Honduras (northern) and the Yucatan Peninsula. Several eddies were associated with his flow system. Niiler (1976) described a pattern of small scale eddies (~150 km diameter) of opposite signs of rotation, drifting north along the junction of the Loop Current and the west Florida shelf, an early examination of this type of feature. Niiler (1976) also contained the results of an investigation into the wind forced circulation on the west Florida outer shelf, which was found to be related to frontal passages. Worthington (1976) is a summary account of his perspective for the general circulation of the North Atlantic Ocean. Ferbes-Ortega and Herrera (1976) is an early on examination of the circulation in the vicinity of the southernmost passages of the Caribbean Sea that is used in Appendix D. DiMego et al. (1976) document the frequency of frontal passages into the Gulf on a monthly basis for 1965-1972.

Maul (1977) described and discussed a type of annual-like cycle in Loop Current penetration. In a 5 year period, 5 warm-core eddies (called LCR's in this review) were observed to separate from the Loop Current, but not at annual period, except perhaps approximately in one case. In one of the figures presented by Maul (1977, his Figure 2, data from May 1972), there was an example of the process of LCR separation, in which a cyclonic intrusion from the southwest had a larger penetration into the Loop Current than an intrusion from the West Florida Shelf, please see Figure 2-15 in this regard. Figure 8 by Maul (1977) indicates the presence of two eddies over the Florida Shelf (in his section on fine-scale features), which he suggested were comparatively small spin-off eddies in the vein of those identified by Lee (1975). These eddies appear to have a different configuration and source relative to the cyclonic intrusions into the LC studied by Cochrane (1969, 1972) and the intrusion from the shelf that is a feature of in Figure 1-3 in this review (please also see Vukovich et al, 1979a; Vukovich and Maul, 1985). There is evidence in Figures 2 and 3 by Maul (1977) for three of the deeply penetrating cyclonic intrusions as emphasized by Cochrane (1972). Maul (1977) also contains the first suggestion (an important contemporary research topic) that the inflow into the Gulf in the upper layers of the Loop Current grows as the Loop Current penetrates into the Gulf, with the needed equivalent outflow occurring below the upper layer flow through the Yucatan Straits [please see Maul et al. (1985), and Chapters 2 and 4 for more information]. Maul (1976) was the publication of earliest date (not referenced by Maul, 1977), to consider the details of a Gulf/Caribbean exchange of water, especially with regard to northerly penetration of the LC into the Gulf, along with subsequent warm-core eddy formation. The database used was about one year of observations in the vicinity of the Yucatan Straits and the LC in the eastern Gulf, in 1972-1973. Behringer et al. (1977) analyzed the available temperature data for the GOM at that time to re-examine characteristics of the latitudinal penetration of the loop current into the GOM, and LCR formation in the eastern Gulf, along with the properties of the quasi-permanent anticyclone in the western Gulf. They found that the interval between LCR separations in their data set varied from 8-17 months, with indications of a typical, but not ironclad, annual cycle in the penetration distance into the Gulf by the Loop Current. They also concluded that there was good evidence in their one degree square based maps of temperature at 200 m depth for persistence of the western anticyclone. Beringher et al. (1977) arrive at the following general picture of the GOM circulation: (1) The large scale quasi-stationary anticyclonic circulation is dominated by the Loop Current in the east and an anticyclonic gyre in the far west, centered at about 24°N, (2) The Loop Current sheds eddies at intervals of 8-17 months, (3) The western anticyclone may be influenced by wind forcing and/or by the remnants of LCR's that propagate to the western Gulf, but more evidence would be needed to sort out the relative contributions. This was pretty much a confirmation of the picture that could be gleaned from maps prepared by Whitaker (1971) and Robinson (1973), but based on more data. Behringer et al. (1977) also noted that although there were some indications of a maximum in the strength of the western anticyclone during the summer and the winter, the evidence was not conclusive.

Carder et al. (1977) acquired and discussed observations of dissolved silica with respect to the circulation in the Yucatan Straits, in which context they used silica data to help "adjust" a geostrophic speed profile across the Yucatan Channel, please see Chapter 2.1. Kundu (1977) concluded that upwelling off the African coast near Spanish Sahara was frictionally dominated, in contrast to the case for upwelling off Oregon. In this case relatively cool water creeps onshore toward the coast along the bottom. Evidence is presented in Chapter 3 of this review indicating that the upwelling off the west coast of the Gulf in summer may be similar to the wide shelf regime off Africa. Morrison and Nowlin (1977) described and discussed the properties of the Loop Current and LCR's based (primarily) on data collected on R. V. *Alaminos* Cruise 72-A-9 in May 1972. During the cruise period the LC was in port-to-port mode and a recently detached warm core ring was to the immediate north and slightly west of the Loop Current, please see Figure 2-15. This data contains one of the few recorded deep or large intrusions or penetrations of cold water from the Campeche Banks into the Loop Current. Molinari (1977) is a compilation of the available data on 21°C isotherm depths in the Gulf, including some other data. Molinari and Yaeger (1977) described the hydrography, surface currents, and transport of the Yucatan Current in May, 1972. Their results were supportive of the estimates of geostrophic currents and transports by Schlitz (1973), and consistent with concurrent measurements in the Straits of Florida. The possibility of a wind-induced exchange between the Cayman Sea and the Gulf of Mexico was considered by Molinari (1978). Blaha and Sturges (1978, 1981) described and discussed several features of the circulation of the GOM, with emphasis on wind forcing in the western Gulf and on coastal MMSL. Following in the footprints of Marmer (1954) and Whitaker (1971), their report in 1978 was the next major contribution to the study of coastal MMSL in the Gulf. Blaha and Sturges (1981) examined the effects of wind-driven (by both stress and curl) flow on coastal sea level around the Gulf of Mexico at time scales from a few months up to annual, dynamic heights were also considered.

Molinari et al. (1978) found a semi-permenant western anticyclone in their maps of dynamic topographies relative to 1000 m, in support of the results by Behringer et al. (1977). Molinari et al. (1978) also estimate that the flow from the Texas Shelf into the northern limb of the western anticyclone is a permanent feature, typically .5 to 1 Sv in the upper 200 m depth range. Kelly (1978) is a Masters Thesis on the circulation in the Tropical Atlantic Ocean that was used in Appendix D. Deep currents in the Yucatan Straits were described by Hansen and Molinari (1979), based on current meter and hydrographic data obtained during a month in the autumn of 1970. Vukovich et al. (1979a) used satellite infrared data from the period 1973-1977, along with some in-situ data, to describe variations in the configuration of the outer boundary of the Loop Current and associated warm core ring formation/separation. They document several examples of meanders along the outer boundaries of the LC, with large amplitude intrusions of water from the direction of the west Florida shelf into the LC, similar to the first such observation based on Parr's (1935) data as presented by Ichiye (1962), please see Figure 1-3. Vukovich et al. (1979a) contains relatively convincing evidence that cyclonic intrusions from the west Florida shelf may be strongly correlated with LCR separation.

These results are supportive of the suggestions made by Cochrane (1972) with respect to the role of cyclonic features in LCR separation. Vukovich et al. (1979a) was a major extension of our knowledge of the physical oceanography of the eastern Gulf, and this publication is heavily used throughout my review. Vukovich et al. (1979b) was a follow on to Vukovich and Crissman (1975), please also see Vukovich et al. (1978), and Vukovich and Crissman (1980). Millot (1979) is a comparative consideration of the effects of coastline geometry on upwelling. Cochrane et al. (1979) was used by Schmitz (1996a) to infer current structure in the tropical Atlantic, as noted in Appendix D. J. Reid (1979) suggested that Mediterranean Water moves north and plays a role in the formation of NADW (North Atlantic Deep Water, please see Figure 4-2 and Appendix D). Renteria (1979) studied upwelling onto the Campeche Bank north of the Yucatan Peninsula, as discussed in more detail in Chapter 3 of this review.

Elliot (1979, 1982) presented a comprehensive view of the circulation of the western Gulf, focusing on rings, on the characteristics of the western anticyclone, on their relation in terms of LCR's being the source of the western anticyclone, and considering wind forcing. He pointed out that Ichiye (1962) had suggested that after pinching off from the LC in the eastern Gulf, eddies might translate westward and interact with the western boundary in the Gulf. Elliot (1979, 1982) noted that the ring formation or separation processes was not actually observed until 1969, as described in a publication by Cochrane (1972). Cochrane (1972) observed ring separation to occur when a large cyclonic (cold) "meander" penetrated the Loop Current from the west Florida shelf and was joined by a similar but smaller (and fresher) "Yucatan Meander". Although warm core eddies in the western Gulf were the primary topic (Elliot, 1979, 1982) of investigation, Elliot (1979) also made major contributions to our knowledge of wind forcing for the western Gulf in general, and presented a pioneering discussion of cyclones in the western Gulf, both topics discussed below and in Chapter 2 of this review. Elliot (1979) also contains an excellent discussion of previous work, and in this regard is a model for the present review. Elliot (1979) examined the suggestion made by Sturges and Blaha (1976) that the western anticyclone might be wind forced. He noted that one of the attractive features of wind-forcing was that one of the anticyclonic features described by Nowlin and McLellan (1967) has an overall east west scale of about 1000 km, seemingly too large to be accounted for by LCR's (or anyway LCR's only), whose diameters are 150-300 km. According to Elliot, at the time of his investigation a study explicitly aimed at determining the frequency of ring formation and their movements after separation had not yet been mounted. There existed at that time only one explicit estimate of propagation speed, westward at 3.7-5.6 km/day, by Cochrane (1972).

Elliot (1979,1982) was able to re-examine existing hydrographic data and document the separation of 3 rings from the Loop Current, and their westward translation, all the way to the western boundary of the GOM for 1 of these warm core rings. He also examined LCR's sizes and life spans, including decay characteristics, and their effects on property distributions in the western Gulf. A variety of evidence was used to indicate that about one LCR per year makes it way into the western Gulf, and that a year is about a ring decay time scale. Molinari (1980) demonstrated that maximum northerly penetration of the Loop Current can occur in any season. The mean dynamic topography of the sea surface relative to 1200 db was shown to contain a small cyclone just east of the average location of the Loop current. Ned Smith began his studies of the South Texas shelf circulation in the mid l970's and continued to publish actively in this area until circa 1980. Hydrographic studies used in Volume I are by N Smith (1976, 1977 a,b, 1978b, 1980a). Moored current measurements on the shelf offshore of Aransas Pass were made by Smith (1975; 1977a; 1978a; 1979; 1980a,b). These measurements were typically short in duration (1-2 months) compared to today's capabilities, and used mostly to examine sub-tidal scale fluctuations driven by the wind, a state of the art procedure in the l970's [see for example Scott and Csanady (1976)]. Smith's studies of the currents on the continental shelf off South Texas brought current meter data to bear on topics that had previously mostly been addressed by drifters. Order days to week variability is perhaps more readily described by current meter data and their statistics as is perhaps the investigation of dynamical balances. Lagrangian measurements may be better suited for spatial coverage of very low frequency current patterns, perhaps especially monthly means, and a practical choice just outside the surf zone (Murray, 1975), a mix of both Eulerian and Lagrangian techniques probably being desirable in many situations.

Smith (1980c) summarized his previous investigations by noting that flow patterns along the Texas Coast can be characterized as having generally north to south flow, often quite strong, between approximately October and April, and a relatively slow alternating flow, with a slight net transport to the north, during the other months, the prevailing view today. He further stated that currents on the Texas Shelf appear to be driven by the alongshore component of the wind-stress. He consistently found that the coherence (only qualitatively established before this) between the wind stress (locally usually, but sometimes regional) and currents were strongest in the alongshore directions and larger near the coast than on the middle shelf. His measurements of the regional scale for this coherence (Smith, 1980b) was a new result for the area in question although the alongshore length scale of the current pattern was qualitatively well known. Smith's publications are considered in more detail in Volume II of this review. Allen (1980) is an early-on review of dynamical models of coastal circulations. Clemente Colon (1980) is a study of circulation features in the western Gulf in the context of satellite and hydrographic data. DeVersey (1980) is an account of very-early-on ideas and views of the general circulation of the North Atlantic Ocean. Vukovich and Crissman (1980) is a study beyond Vukovich and Crissman (1975) on the use of satellites in the study of western boundary or frontal eddies in the Gulf Stream. Roemmich (1981) is a valuable study of the circulation of the Caribbean Sea using an inverse model. Bane et al. (1981) is an example of studies of frontal eddies between Charleston and Cape Hatteras, which could have implications for similar investigations in the Gulf, please also see Lee et al. (1981). According to Chew (1981), the warm filament in a shingle on the inshore edge of the Florida Current is a surface trapped anticyclonic feature, and at depth the associated cold core cyclone intrudes into the Gulf Stream as a result of upwelling.

Important benchmark investigations for the GOM in the early 1980's are the basic dynamical explanations of the formation of rings (Loop Current Rings, LCR's) in the Loop Current Regime, as well as some of the characteristics of the resultant warm-core eddies by Hurlburt and Thompson (1980, 1982). The results they obtained are discussed in much detail in Appendix C, as well as Chapters 1 and 2. These kinds of studies were pursued by these authors and their colleagues throughout the 1980's and early 1990's, which are included in Appendix A.2 as well as nearly all other sections of this review. Kassler and Sturges (1981) described the circulation in the western GOM based on new data acquisition over a years duration involving 6 AXBT flights, 5 cruises, moored current meter observations, plus the historical data-base. The main results according to Kassler and Sturges (1981) were the identification of a background presumably wind-driven circulation of 5-10 Sv, involving a western boundary current, along with the presence of warm-core eddies, the latter also observed to interact with the slope-rise topography. This report is discussed in detail in Chapter 2. Molinari et al. (1981) is a depiction of the general circulation of the Caribbean Sea based on drifter data, please see Chapter 4 and Appendix D. Huh et al. (1981) observed an intrusion of cold water up DeSoto Canyon and onto the West Florida Shelf. Merrel and Morrison (1981) pointed out that the currents in the western Gulf were unexplored relative to those in the eastern Gulf. They noted that most previous data acquisition in the western Gulf [as reviewed for example by Nowlin (1972)] had involved survey cruises with rather wide station spacing. Merrell and Morrison (1981) give a balanced account of the status of identifying the mechanisms responsible for the western anticyclone, recognizing the pioneering ideas by Ichiye (1962), and make the very interesting suggestion that cyclones a well as anticyclones may be propagating into the western Gulf from the eastern Gulf just west of the LC. Merrel and Vázquez (1983) continued the investigation by Merrel and Morrison (1981) to include a second cruise in the western Gulf in March 1978. On the second leg of this cruise (Merrell and Vázquez, 1983) a cyclonic feature was also partially crossed, to the south of the semi-permanent western anticyclone.

A combined ship and satellite examination of the circulation in the western Gulf by Brooks and Legeckis (1982) identified in April 1980 the cyclone/anticyclone pair typically found up against the slope in the western Gulf. A cyclone was centered at about 26.5°N and 95°W and the warm core ring-like feature was centered near 23.5°N and 95.5°W. These authors concluded that the western anticyclone originates from the Loop Current due to its subtropical underwater signature. Brooks and Legeckis (1982) also observed a front between the cyclone and the anticyclone that they identified as the locus of a flow off the shelf of comparatively fresh water, a good example of Shelf-Gulf interaction, please see a more detailed discussion of this result in Chapter 3 of this review. Schmitz and Holland (1982) presented the first detailed intercomparison between the results from idealized eddy-resolving numerical experiments with the data base in the mid-latitude jet region of the Gulf Stream. Sanford et al. (1982) is the baseline reference on electromagnetic dropsonde techniques and interpretation. Mitchum and Sturges (1982) is an important paper with respect to the wind driven flow on the west Florida Shelf, with significant implications for the Texas Shelf. Duncan et al. (1982) presented an updated picture of the near-surface circulation in the Caribbean (and the Antilles Arc in general), as derived from geopotential topography based on about 4000 stations involving hydrographic data from the US Oceanographic Data Center. Molinari and Mayer (1982) studied current meter results from the continental slope in the eastern GOM, with one mooring offshore of Mobile, Alabama and another off Tampa, Florida. In addition to wind forcing, it was noted that the Loop Current impacted these sites. The flow at the near-bottom current meters was aligned along topography as expected.

Paluszkiewicz et al. (1983) identified a Loop Current intrusion onto the west Florida shelf, based on hydrographic and satellite data collected over a week in the spring of 1982. This feature, a specific example of interaction between a western boundary current regime and a continental shelf environment, was taken to be at least somewhat similar to Gulf Stream frontal or spin-off eddies as observed on the east Florida shelf, except that the associated upwelling was not as intense in the Gulf. An eddy was found to propagate toward the southeast (roughly along the cyclonic shear boundary of the LC and/or the shelf break) at about 30 cm/s and was associated with upwelling. This eddy may be similar to those noted by Maul (1977). This eddy is probably not similar to the cyclonic intrusions into the LC from the west Florida Shelf (Cochrane 1969, 1972; Vukovich et al., 1979a) that may be associated with separation of warm core rings (please also see Vukovich and Maul, 1985). Morrison et al. (1983) studied the deep property distributions in the western Gulf. Csanady and Shaw (1983) is a rather early-on article discussing the dynamics of how disturbances originating in the Gulf Stream system might interact with continental shelf and slope regimes. Lee and Atkinson (1983) studied frontal eddies along the outer continental shelf of the southeastern U. S. Sturges and Evans (1983) pieced together a 13 year record of the northernmost positions of the Loop Current, using mostly hydrographic observations and to some extent satellite data. They found that the "annual" variation of the northward penetration of the LC is more like a broad spectrum from 8 to 30 month periods, as opposed to a spectral line at annual period. Thompson et al. (1983) examined the results of using altimetry data in conjunction with a numerical model of the GOM. Allen et al. (1983) reviewed the state of the art at that time for the physical oceanography of continental shelves in general. Hurlburt (1984) contained a timely review of the role of satellite altimeter data in ocean circulation forecasting. As an important aside, he presented results for a 2 layer numerical simulation that may play a role in our perspective of the Gulf circulation, as discussed further in Appendix C and Chapters 1 and 2. Wallcraft and Thompson (1984) compared their model results favorably (in general terms) with drifter observations. Crepon et al. (1984) considered the effects of coastline geometry (especially capes) on upwelling. Kirwan et al. (1984a,b) discussed drifter data in warm core rings in the Gulf. Brooks (1984) examined the results of a current meter array deployed for 7 months in mid-1980 to early-1981 in the 200-700 m depth range over the upper continental slope east of the South Texas Shelf. This moored array was deployed somewhat north and west of a western anticyclone, which was observed to weaken between hydrographic surveys. Results from one of these surveys, along with SST data, were used by Brooks and Legeckis (1982) to demonstrate the offshore movement of cool fresh water from the continental shelf in the western Gulf at the juncture of a cyclone - anticyclone pair near 25°N. Previous examples of observations of offshore extending tongues of fresh water between 23-26°N may be attributed to Nowlin (1972), and Clemente-Colon (1980). Brooks and Legeckis (1982) is referred to extensively in this review, please see Chapter 3 for example. Brooks et al. (1984a,b) analyzed current meter data from the array described by Brooks (1984) along with data from several sites on the continental shelf and slope (their figure 3-1) in the northwestern Gulf, including a site along the 80 m depth contour offshore of Mustang Island, Texas. The actual SST maps and the basic current meter results (data time series) are in Brooks et al. (1984b), and interpretive results are in Brooks et al. (1984a). The effects of the presence of the western anticyclone in the process of decay were possibly detected in data from the moorings deployed by Brooks (1984).

Brooks et al. (1984b) also contains a variety of satellite SST maps that have interesting patterns of frontal eddies are concurrent to some extent, also a bit later but similar to the images described by Vukovich and Maul (1985), as well as Vukovich and Crissman (1986). Their Figure 5-8, an SST map for 30 April 1981 contains a deeply penetrating cold feature in the LC from the north and northeast, analogous to similar figures by Vukovich and Maul (1985). A warm eddy with a shingle on its northern side was shown to separate about a month later (Figure 5-11, May 28, 1981). Figure 5-14 (SST map for 4 March 1982) by Brooks et al. (1984) is similar to later SST maps by Fratantoni (1998), which suggest the propagation of a Tortugas Eddy into the northern segment of the southern Straits of Florida, please also see their Figure 5-15. The section on SST maps in Brooks et al. (1984) contains examples of the separation of comparatively small warm-core eddies from the northern regions of the LC boundary as well as the separation of large conventional rings from the southern locations. Their Figure 5-18 [Brooks et al. (1984b), a SST map for 21 December, 1982) contains a cyclone pair at the throat of the LC near the Yucatan Straits that is very similar to the canonical pair emphasized by Cochrane (1972). In their SST map for 28 December, 1982 (Figure 5-19 by Brooks et al., 1984), a warm core ring had just separated from the LC. In their map for June 21, 1983 (Figure 5-25, Brooks et al., 1984b), the eastern member of the Cochrane (1972) cyclone pair was extended across the LC. In their Figure 5-32 (an SST map for February 21, 1984), there is an extended cold perturbation into the LC off the west Florida shelf that was very similar to those examined by Vukovich and Maul (1985). Shingle-like cyclonic features were frequently present on the boundary of the LC and LCR's in many of the SST maps in Brooks et al. (1984b).

END OF SECTION 1 FOR APPENDIX A, LAST UPDATED 22 FEBRUARY 2003.