CHAPTER 1: AN INITIAL SURVEY

SECTION 3

Organizational Notes for Chapter 1 are contained in this paragraph: Section 3 of Chapter 1 (called 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 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) contained a preamble that considered mostly general background information, including some historical remarks, and then moved into an introductory survey, primarily for the eastern Gulf, of the Loop Current and its Eddy Field (collectively called the Loop Current System or Regime in this review). Part 2 of Chapter 1 (Chapter 1.2) was a preliminary consideration of processes and mechanisms and numerical model results for the GOM, mostly for the eastern Gulf, but also including an initial view of some of the important processes in the western Gulf. Chapter 1.3 was last updated on 22 November 2003, and there are about 13 pages and five illustrations involved (Figures 1-20 through 1-24). Page and figure numbering is by Chapters, not Chapter Sections. Figures are contained in sections following the corresponding text.

Proceeding on with an initial general survey of the general circulation in the Gulf of Mexico (the focus of Chapter 1), a preliminary view of coastal circulations in the northwestern Gulf that are also involved with offshore circulation features is developed now. Chapter 3 considers in more detail some preliminary examples involving remote forcing of coastal circulations in the Gulf, topics to be examined thoroughly in Volume II. The continental shelf circulation off the upper Texas and Louisiana Coasts has been the site of comparatively extensive data acquisition over the years. Various investigations in the 1960's and 1970's that identified some of the characteristics of the shelf circulation in the northwestern Gulf (for example, Kimsey and Temple, 1963, 1964; and Smith, 1975, 1977b, 1979) were followed by a very good descriptive and dynamical summary of the circulation on the LATEX (Louisiana-Texas) Shelf published in the 1980's (Cochrane and Kelly, 1986; typically abbreviated as CK86 in this review). Preliminary glimpses of the evolution of the CK86 picture may be found, for example, in reports by Kelly et al. (1980, 1982, 1983). Recently, a comparatively polished dynamical picture was put together by Oey (1995) using a numerical model in process mode, although the 20 km horizontal resolution that he used is coarse to say the least. According to Oey

(1995), the Latex Shelf Circulation is driven by wind and buoyancy forcing, in conjunction with interactions with the larger scale circulation (eddies) in the western GOM, please also see Ohlmann et al. (2001) in the latter context. The large-scale wind forced circulation in the western Gulf (Sturges and Blaha, 1976; Blaha and Sturges, 1978, 1981; Elliot, 1979, 1982; Kassler and Sturges, 1981; Wallcraft, 1985, 1986; Sturges, 1993; Oey, 1995) is discussed in Chapter 2.7 and in Appendix C. Chapter 2.7 contains a suggestion that the western Gulf is more like a eddy-rectified type of recirculation regime, in partial analogy to the Gulf Stream System (Schmitz, 1996a, for example), as opposed to the Sverdrup balance type of subtropical gyre region that is classically taken to be the zero order dynamical regime in the (eastern) interior of the North Atlantic Ocean. The flow over the inner and middle shelf in the northwestern Gulf is probably mostly wind and buoyancy driven, but the return flow (or recirculation) and exchange with the Gulf on the outer shelf is strongly influenced by anti-cyclones and cyclones over the continental slope and rise (Hamilton, 1992, 1998; Hamilton et al., 1999, 2002; Niiler, 1999; Oey, 1995; Ohlmann et al., 2001), please see Figure 1-21 and vicinity. The flow on the LATEX Shelf also interacts with a combined wind and eddy rectified anticyclonic upper level circulation in the deep western Gulf, and is also connected with currents associated with upwelling favorable winds at some times and locations. The major buoyancy source on the Louisiana-Texas Shelf Regime is the discharge of the Mississippi River System. The LATEX region has also been the site of extensive data acquisition in the 90’s (for example: Cho, 1996; Cho et al., 1998; Halper et al., 1998; Hamilton et al., 1992, 1998; Jochens, 1997; Li et al., 1996, 1997; Lo, 1998; Murray, 1997; Murray et al., 2001; Niiler, 1999; Nowlin et al. (1998a,b); Sahl et al., 1993; 1997; Wang et al., 1998). Publications during the 1990's on the LATEX Shelf circulation tend to mostly confirm the basic characteristics (not necessarily details, especially regarding dynamical specifics, and offshore circulation closure) of the CK86 scheme. The reader interested in recent observations related to the Louisiana-Texas Shelf Circulation could consult Murray (1997) and Nowlin et al. (1998a,b) as starting points. Although a comparatively complete picture is now available for the LATEX downwelling regime, the least well-defined circulation features are still associated with its open boundaries, that is, the characteristics of remote forcing or interactions, especially those involving the recirculation or closure (Current and Wiseman, 2000) of the coastal jet. A good early on visual example of the exchange of water between deep flow features (a cyclone/anticyclone pair) and the shelf circulation in the western Gulf (Brooks and Legeckis, 1982) is shown in Chapter 3. A distinct tongue of low salinity shelf water was observed as early as 1962 (Nowlin and McLellan, 1967) to extend offshore at the surface near 24-25°N in the western Gulf (Chapters 3 and 4 and Appendix A). In Chapter 1, and especially in Chapter 3, the Texas-Louisiana Shelf and its extension southward are used to examine in a preliminary way some of the types of remote interactions or forcing that will be considered in detail in Volume II.

Figure 1-20: Monthly mean alongshore currents, along with the alongshore component of wind stress, at a site on the inner shelf near Freeport, Texas.

Figure 1-20 is a sketch of the monthly mean alongshore winds and alongshore current components at a site just offshore of Freeport, Texas, as adapted from a figure by CK86. Blaha and Sturges (1978) had demonstrated a correlation between the alongshore component of the wind stress and monthly mean sea level at Galveston, Texas (that is, on the LATEX shelf). Circulation-wise, the annual cycle on the LATEX inner and middle shelf follows the pattern of the alongshore component of the local and regional wind fields and is characterized on the average by flow turning a corner near 28°N, counter clockwise and down the coast (a component directed toward the south) in the non-summer months (from September to May, say), a prototypical downwelling regime, relaxing in May-June. When the winds associated with frontal passages from the fall through the spring months relax, the high sea level along the coast associated with the strong downwelling regime also relaxes and sea level at the coast rapidly decreases. Winds are sometimes favorable for coastal upwelling at locations along the Texas Coast during the summer months, as first pointed out by Franceschini [1953, please see Kelly (1988a,b) for a clear example, which is also presented in Chapter 3]. CK86 also contains a nice discussion of the summer season and associated upwelling possibilities in the vicinity of their Figure 14. In addition, CK86 note how in the summer season the winds tend to pin or pond the Mississippi Discharge up against the northwestern Gulf Coast, and point out the rather abrupt release of this low salinity water as a buoyant jet down the coast when frontal systems and associated winds develop in September. From approximately June through August, winds with a component from the south can lead to an alongshore component of the wind field that can induce flow up the Texas Coast, possibly associated with upwelling (please also see Angelovic, 1975; Murray (1997), and Nowlin et al., 1998b), with local wind forcing becoming rather weak on the average at Freeport (Figure 1-20).

Figure 3 in Chapter 3 is a plot of the monthly mean alongshore wind stress moving down the Texas Coast (according to CK86). The seasonality of the flow on the inner and middle shelves in the western Gulf is spatially inhomogeneous from north to south, partially as a result of geographic inhomogeneity in the seasonality of the alongshore component of the wind field indicated in Figure 3-3. Along the coast in the western Gulf, wind-wise as well as temperature-wise, “summer” arrives sooner and frontal passages are less numerous moving south. There is a strong alongshore and temporal variation (inhomogeneity) in the general characteristics of the stratification on the shelves in the western Gulf (which is determined mostly by salinity when and where fresh water discharge is prominent). This is especially significant with respect to the discharge of the Mississippi River System, which can penetrate quite far down the coast in the western Gulf [please see Angelovic (1975, Table 7 there)]. South of the mean point of penetration of this plume down the coast, the density field is more strongly determined by temperature. Eddies are present over the slope and interact with coastal circulations in any season. Sahl et al. (1993, 1997) have discussed upwelling due to bottom currents associated with eddies and currents in general in the westernmost Gulf. They also examined the water exchanged between the shelf and deep Gulf associated with cyclone-anticyclone pairs over the continental slope in the vein of Brooks and Legeckis (1982).

Smith (1978c) discussed the hydrographic data that he acquired along a transect across the continental shelf off Port Aransas, Texas (please see Figures 1-23 and 3-13) in terms of coastal upwelling. There has been surprisingly little other work published on coastal upwelling for this region [notable exceptions are Angelovic (1975), Murray (1997), and Nowlin et al. (1998b), as well as Smith (1977c, 1980)]. Even less is available that explicitly focuses on possible deep ocean linkages with coastal upwelling in the central westernmost GOM (please see Chapters 3 and for more discussion in this regard). Interesting order days to a couple of weeks variability (Smith, 1977b, 1979, 1980b) have been observed along the coast in the western Gulf (to be discussed in detail in Volume II).

Niiler (1999) used surface drifter data accumulated on the LATEX Shelf and over the continental slope and rise regime offshore during the downwelling regime in an examination of the ability in "deterministic predictive mode" (a hindcast with concurrently measured winds but no data assimilation), of a particular class of numerical models (Herring et al., 1999). In general terms, the model currents on the LATEX inner and middle shelf were about 30 % too low in amplitude but consistent in pattern there with the Niiler (1999) observational results. However, over the continental rise and slope and shelf break, the model circulations were fundamentally divergent from the drifter database (please seen Appendix C for more detail). The model-data intercomparison results presented by Niiler (1999) constitute an important observational assessment relative to predictive capability on and immediately offshore of the LATEX and South Texas Shelves, as discussed in Appendix C. Approximately 400 surface drifters were deployed and tracked. The period of largest data density and pattern persistence, September 1993 to April 1994, was selected by Niiler (1999) as the priority for intercomparison purposes, and is now schematically summarized here (Figure 1-21) in order to further examine observationally the pattern of near surface mean flow as observed for the non-summer months when the LATEX shelf circulation is in its downwelling regime. The observations collected by Niiler (1999) are to a large extent a confirmation of some of the basic results by Cochrane and Kelly (1986), but also a significant new contribution to the database and descriptive and dynamical (please see Ohlmann et al., 2001) perspective for the northwest GOM, primarily with regard to eddified recirculation path(s) for the LATEX downwelling regime. Recirculation patterns are at least partially associated with an eddy field (Oey, 1995), characterized by small or medium sized cyclones and anticyclones over the continental slope [please see Hamilton (1992, 1998) and Hamilton et al. (1999, 2002)]. Figure 1-21 is a qualitative characterization for illustrative purposes of the time averaged flow pattern for the non-summer circulation on the Texas-Louisiana Shelf, ignoring flow strength, as determined from the surface drifter data acquired and presented by Niiler (1999, his Figure 7.2). On this figure the green lines indicate shelf or possibly shelf related flow, blue indicates cyclones on the continental slope and the red line suggests the presence of the western anticyclone. The dashed green line indicates weaker currents. The light blue line indicates a flow feature that could involve a mixture of shelf and Gulf water in a smaller anticyclone that is not well defined for the data in question. Figure 1-21 highlights the long-term existence of medium sized cyclones over the slope offshore of the LATEX shelf. These are the features missing from the CK86 picture as well as the numerical model results presented by Niiler (1999).

Figure 1-21: A schematic of the time-average flow pattern on the LATEX and South Texas Shelf and slope-rise regions for the non-summer months, based on surface drifter data.

To the best of my knowledge, the moderate sized cyclones on the continental slope in Figure 1-21 have not yet been explicitly demonstrated in any numerical model results. Similar cyclones and anticyclones to those depicted in Figure 1-21 have been observed by several investigators in the past at a variety of locations in the vicinity of the LATEX area shelf/slope regime [for example, figure A-7, adapted from Nowlin (1972), contains a cyclone pair in the northwestern Gulf in the vicinity of the continental shelf-slope system there]. According to Hamilton (1992, 1998), and Hamilton et al. (1999, 2002), which are the major publications on cyclones associated with the continental slope-shelf systems in the northern Gulf, the origin of these cyclones is open to question, although the exchange mechanism between the deep and shallow Gulf is thought to be associated with cyclone/anticyclone pairs. Perhaps one possible process might involve cyclogenesis of an offshore jet originating near the Rio Grande Delta as a turning point for the downwelling regime in Figure 1-21 ([lease also see figure 84a by Murray, 1997). This flow could perhaps wrap around in the cul-de-sac in the northwestern Gulf (some SST's exhibit this possibility, please see Chapter 3.2). In addition, an offshore jet near Brownsville (a front perhaps) often found in the summer months may wrap around to form a cyclone in the LATEX Bight. The presumed shelf-related circulation (shown in green) in the data (Figure 1-21) indicates onshore/offshore flow induced by cyclones and the junction between them and the western anticyclone, please also see Chapters 3 and 4. Figure 1-21 suggests that the recirculation or offshore limb of the Latex Downwelling Gyre might be sinuous as opposed to a well-defined shelf break current [please also see Hamilton et al. (1999, 2002)]. Figure 1-21 demonstrates that cyclones and possibly anticyclones of moderate size do play a prominent role in Shelf-Gulf interactions in the westernmost Gulf. Although the offshore or recirculation path for the Latex Downwelling Gyre may be dominated by moderate-sized cyclones over the slope, the turning point near Brownsville in Figure 1-21 may have a different origin (involving the bottom topography associated with the delta of the Rio Grande River System). Note that in the data contoured in Figure 1-21, a return flow onto the easternmost region of the LATEX Shelf was not observed, so the flow is not closed in this data set, as indicated by a question mark (in green on Figure 1-21) at the eastern end of the LATEX Shelf. The turnaround point for the downwelling gyre near the Rio Grande River Delta in Figure 1-21 is reminiscent of the classical results by Nowlin (1972) and Brooks and Legeckis (1982), although this review (I think) contains the first emphasis on the influence of the delta topography, as discussed in Chapter 3, and summarized in Chapter 4. One example of

Shelf-Gulf interaction was just considered, for the LATEX region in the non-summer season, involving the influence of deep water cyclones and anticyclones on outer shelf current patterns (Figure 1-21), where they may play a role in closing the circulation that is associated with the wind and buoyancy driven flow in a strong downwelling regime (CK86) on the inner and middle shelf there (Jochens, 1997; Oey, 1995). So a wind and buoyancy driven coastal circulation may interact strongly with eddy driven flows on the outer shelf and slope. Another type of Shelf-Gulf coupling that may be of interest is the interaction of the large scale wind field over the Gulf with coastal circulations. An example of this possibility, introduced here and considered further in Chapters 2 and 3, may also be connected to summer upwelling in the western Gulf, This topic hasn't received much attention for some reason, even though it was pointed out quite early on by Franceschini (1953) that the wind field in the western Gulf tends to be upwelling favorable in the summer months. Angelovic (1975) called attention to the Brownsville area as potentially upwelling favorable, and an informative recent study of this region was published by Nowlin et al. (1998b). Upwelling off the LATEX coast has been studied a few other times in the past [CK86, Jochens (1997), Kelly (1988a, b); McLellan (1960); Murray (1997); Sahl et al. (1993, 1997)], in some cases eddy driven. Kelly (1988a, b) contains the best specific example of wind-driven upwelling on the LATEX Shelf that I am aware of (this example is shown in Chapter 3). "Upwelling" may also be a result of eddy-topographic interaction (Sahl et al., 1993, 1997), that is, onshore flow induced in an Ekman layer along the bottom by an encroachment of an anticyclone on the shelf break and/or continental slope (Brooks and Legeckis, 1982), or by a western boundary current, either wind or eddy driven or both (for example Sturges and Blaha, 1976; Sturges, 1993). Jones et al. (1965) carried out a year long hydrographic survey (nominal) 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 toward the coast from the outer shelf in May and June, and continuing in July.

Figure 1-22: A temperature section off Mustang Island, Texas from early December, 1976.

Reports by Smith (1977c, 1978c) are pertinent to our picture of coastal upwelling in the summer along the South Texas Coast (please also see Smith, 1980). Some of the evidence obtained by Smith (1977c, 1978c) is considered now, in terms of contrasting winter and summer conditions on the continental shelf off Port Aransas (Smith, 1977c). Looking for the moment at winter conditions on the South Texas Shelf, a hydrographic section just south of Port Aransas by Smith (1977c, his Transect II) for December, 1976 is shown in Figure 1-22. In this figure, the red vertical lines indicate station locations, blue lines are isotherms in the 15-18°C range, and green lines isotherms in the 19-21°C range. The winds in this area in the winter season tend to have a strong alongshore component (down the coast) on the average (winds from the northerly and easterly quadrants associated with frontal passages), and the temperature field is essentially vertically homogeneous on the inner and middle shelf (as illustrated by the data from December, 1976 in Figure 1-22), with a pronounced mixed layer down to about 75 m depth offshore. This is characteristic of the downwelling regime in the northwestern Gulf on the South Texas Shelf referred to earlier. In contrast, during the time frame May-June to August-September, the winds along the South Texas and Mexican coasts from about 22° to 28°N may occasionally tend to develop a quasi-persistent alongshore component up the coast, the transition (Figure 3-5) marching from south to north. These "summer" winds tend to be upwelling favorable (and can exhibit strong time-dependence, please see Chapter 3), and are often part of a large-scale wind field (the southwest corner of the Bermuda - Azores High; please see figure C-19, and Franceschini, 1953; Leipper, 1954b; Guiterrez de Velasco and Winant, 1996; Sturges, 1993). In the summer regime as depicted in Figure 1-23 for August 1976, isotherms become slanted relative to Figure 1-22, having moved or crept up along the bottom to the inner shelf from offshore, as was the case in the observations collected by Jones et al. (1965), with some (but not a lot of) surfacing of isotherms offshore. The vertical red lines in Figure 1-23 denote station locations, blue lines indicate isotherms in the temperature range 18-24°C, and green represents the temperature range 26-29°C.

Figure 1-23: A temperature section across the continental shelf off Corpus Christi, Texas for August 1976.

Comparing Figures 1-22 and 1-23, temperatures in the summer relative to the winter are roughly 10°C warmer over the inner and middle shelf, and offshore the 20°C isotherm is roughly at the same depth winter and summer. In Chapter 3, in analogy to the results presented in Figure 1-23 above, isotherm depth observations acquired in the summer of 1977 are presented in Figure 3-13, and some interannual variability may be implied, please see further discussion of these two figures in Chapter 3.Coastal pilot charts (Sturges, 1993) for the summer season indicate a broad (in longitude scale) ocean circulation toward the north over the latitude range of about 22-27°N in the westernmost Gulf (Figure 3-10), perhaps associated with wind induced upwelling, both on the shelf and offshore. In the coastal areas off Texas and eastern Mexico, upwelling induced by rings or anticyclones originally formed in the Loop Current Regime, and having propagated into the westernmost Gulf, is also likely, and various possibilities are considered in more detail in Chapters 2 and 3 (also Volume II). A near bottom current meter array was deployed along a section located close to that associated with Figures 1-22 and 1-23, but in July through December, 1984 (Wadell and Brown, 1986), also discussed further in Chapter 3 and Volume II of this review. The GOM temperature climatology for August by Herring et al. (1999) contains a lifting of the 28°C isotherm approaching the coast from the deep Gulf off Corpus Christi, Texas, with an offshore lens of 29°C water, something like Figure 1-23. The temperature climatology by Robinson (1973) suggests various areas of upwelling in the summer for the western and southern Gulf, as described and discussed by CK86. In Figure 1-23, some isotherms appear to be creeping inshore along the bottom with others having moved offshore at or near the surface (a distance from the coast of perhaps 50 km as reflected by the 29°C isotherm, possibly with multiple branches), and there is an eddy-like feature between the third and fifth stations offshore. The adjustment of the density field in the transition between the downwelling and upwelling regimes (which may be slow relative to the transition to the downwelling regime in the fall) probably plays a role in the observed typical summer minimum in coastal sea-level (Marmer, 1954; Whitaker, 1970; Blaha and Sturges; 1978), which in its initial stages could be explained by a relaxation and breakdown in the non-summer downwelling regime near the start of the summer season.

In Chapter 3, it is suggested that the upwelling regime on the Texas Shelf off Port Aransas as well as other shelf regimes down the coast in the western Gulf (perhaps especially in the vicinity of Brownsville and south toward Tampico) could be somewhat similar to the coastal upwelling regime for the Northwestern Africa Shelf (Badan-Dangon et al., 1986; Barton et al., 1977; Hughes and Barton, 1974; Smith, 1981, 1995), in that both are “wide-shelf regimes”, as discussed in Chapter 3 (Figure 3-16). The best known upwelling region in the Gulf of Mexico is probably the Campeche Banks System. Welsh (1996) has recently considered this area, another possible example of current (the Loop Current) induced upwelling in conjunction with the classical wind-driven case, please also see Cochrane (1967, 1969a), Furnas and Smayda (1987), Merino (1997), and Ruiz-Renteria (1979). As noted earlier, intensive long term investigations of the upwelling process have not been mounted along the coastal regime in the westernmost Gulf, in sharp contrast to the case for many other seasonal upwelling regimes in the coastal oceans of the world (for example, Allen et al., 1983; Smith, 1981, 1995). It is demonstrated in Chapter 3 (and a preliminary example is shown in Figure 1-24) that the coastal area between Tampico, Mexico and Brownsville and Port Mansfield, Texas is potentially a fairly strong summer upwelling regime (including an offshore jet), typically not as strong when extending up the coast to the vicinity of the section shown in Figure 1-23. Evidence for a stratification pattern off the South Texas Coast in the vicinity of Corpus Christi, Texas that might be related to summer upwelling has just been presented in Figure 1-23, based on a hydrographic section in August 1976. This data was acquired as part of a large observational program (The South Texas Outer Continental Shelf Study) and in a book that summarized the results of the program (Rablais and Flint, 1981), the upwelling implied by these sections was considered to be episodic and of minor significance. At the present time however (early 2001), SST images from satellites are available for several years, and in fact SST maps from as far back as 1982 were used by CK86 in a discussion of upwelling in the northwestern Gulf. As a specific introduction to what might be found in the upwelling context, please consider Figure 1-24, an edited (7 day composite) SST image for 8 July 2000 that has been acquired and processed as described earlier in Chapter 1 for Figure 1-10. Insofar as I can tell (other maps are presented in Chapter 3), this SST pattern, with some variations, is typical of the summer season in the western Gulf (although there may be quite a bit of interannual as well as diurnal and order day variability in this regard). In Figure 1-24, temperatures are color coded as indicated at the top of the map, blue and blue-green regions indicating that colder water occupies segments of the coastal waters in the western Gulf as well as on Campeche Bank. Orange colors denote warmer water (~30-32°C), and the transition areas are green and yellow. The blues and greens in the vicinity of the Campeche Bank are indicative of the well known upwelling regime there. There are also patches of cooler water along the coast of Campeche Bay from about 92.5°W up along the shoreline of the western Gulf to about 22°N (vicinity of Tampico, Mexico), and a very deep blue region with an offshore jet from approximately 24° to 26.5°N.

Figure 1-24: SST Map for 8 July 2000 (based on approximately a seven day blend of satellite-derived data). Temperatures are color coded as indicated by the bar at the top of the figure.

For now, our focus is on the coastal strip of cool water north of Tampico from about 23°N to 28°N in Figure 1-24. The structure of this band has varied in detail throughout the past few summers but the general pattern is typical, although the intensity tends to be interannual. More evidence for this surface temperature pattern is presented in Chapter 3, Figure 1-24 is meant to be an introduction. The coldest surface water (blue) tends to reside between 24-26°N most of the summer, although similar temperatures are also found between Brownsville and Port Mansfield, around 26-27.5°N. An offshore jet near 26°N is present much of the summer, and persists quite a ways out to sea, possibly involved with an cyclonic-eddy-like feature on the inshore edge of the northerly segment of the offshore extension of this jet. As noted previously and discussed in more detail in Chapter 3, an offshore jet in the vicinity of Brownsville may be a common occurrence (this jet is present in the set of summer SST maps taken in 1982 and presented by CK86 in their Figure 14), and may occur at various times throughout the year, as a turnaround point for both the downwelling and upwelling regimes. This offshore jet may be involved with topographic contours associated with the Rio Grande Delta and with changes in shelf width. Somewhat similar observations of the influence of river deltas on summer upwelling along the New Jersey Coast have recently been documented by Glenn et al. (1996). Barth et al. (2000) contains a data-based examination of the separation of a coastal upwelling jet from the coast near Cape Blanco, and its connection to the California Current System. North of roughly 27.5°N up to about 28.5°N there is a coastal strip of weaker (more green than blue) upwelling in terms of temperature contrast, and multiple jets of cooler water are present there, as is the case in several SST maps (again Figure 14 by CK86). This is the area from which the summer temperature sections from the 1970's are available (Smith, 1977c, 1978c). There is a TABS Buoy (called J) more or less permanently moored roughly offshore of Brownsville, Texas near 26°N, 97.3°W. The data record from this buoy in the period 5-10 July 2000 yields upcoast surface currents on the average, consistent with upwelling. The surface temperature is between 25-27°C (in line with Figure 1-24), including a diurnal variation, and there are both offshore and onshore current components at tidal periods. The winds measured at the NDBC buoy offshore of Brownsville in the time frame of Figure 1-24 were mildly upwelling favorable with a prominent diurnal wind cycle. The coastal strip from 24°-26°N is the strongest coastal upwelling location in the westernmost Gulf temperature wise in Figure 1-24, and in the data that will be examined in Chapter 3. The upwelling regimes present in Figure 1-24 (for 8 July 2000) are also variable on a variety of time scales. For example, when comparing conditions 10 days later on 18 July (Figure 3-19), there is a noticeable change that will be articulated in Chapter 3. The changes during the summer season for 2000 tend to be in terms of intensity as opposed to overall pattern. A SSH map for 4 July 2000, near the middle of the SST composite in Figure 1-24 has a LCR in the western Gulf centered near 26°N and 95.5°W, almost due east of Brownsville, perhaps in a favorable position to participate in the upwelling there. Similar SSH maps presented in Chapter 3 indicate that one or more Loop Current Rings and their by- products were situated off the Texas and Mexican coasts from May to September 2000, so that both ring and wind induced upwelling may have been present. This location for a warm core eddy is a highly probable characteristic of the westernmost Gulf [for example, Figures 3-5 and 3-6, based on Brooks and Legeckis (1982)]. The coastal area near Brownsville was identified as upwelling favorable [Cochrane and Kelly (1986), their Figure 14] in the summer, as well as by Angelovic (1975) and Nowlin et al. (1998b). The introduction to a potentially very interesting and comparatively unexplored upwelling regime in the westernmost Gulf just presented is amplified in Chapter 3, focusing to some extent on the area centered at the border between Mexico and Texas. The area near Brownsville may also be a key turnaround area (Chapters 3 and 4) for the Latex Downwelling Gyre, and variations in bottom topography may be important in this context as well.

Brief Summary of Chapter 1: In this chapter, the reader has been exposed to many of the processes, ideas, and elements that are present in the database associated with the general circulation in the Gulf of Mexico, which is dominated by the Loop Current (LC) and its Eddy Field. The primary and most energetic elements of this eddy field originate from within the LC, large warm core eddies or rings of current called LCR's in this review. These large anticyclonic current rings, as well as smaller warm-core eddies, are cleaved from the LC regime by deeply penetrating cyclones along the boundary of the Loop Current, which are related to the development and amplification of frontal eddies. LCR's detach from the LC and propagate into the western Gulf and decay along their path and at the western boundary as a result of various interactions. SSH data based on routine acquisition of satellite altimetric observations (maps) over the past several years, in conjunction with in-situ data, have shown that the GOM is extensively populated by a diverse spectrum of cyclones and anticyclones. Efforts were made, and will continue to be pursued throughout this review, to put the LC and its eddy field in the context of their role and location in the Western Boundary Current Regime of the North Atlantic Ocean. Numerical model results that show some promise in accounting for the primary processes determining the general circulation of the GOM have been discussed in Chapter 1 in a preliminary way, and their limitations briefly described. These kinds of results are discussed in more detail in Chapter 2.4, Appendix C, and Chapters 4.2 and 4.3. Brief explanations of how this review is put together along with reasons for its organization were given earlier in Chapter 1. Most of the topics introduced in Chapter 1 are amplified upon in Chapter 2, and Chapter 3 extends the discussion to Shelf-Gulf Interactions. A more complete outline of the contents of this review follows.

An Outline of this Review: Volume I focuses on the main characteristics of the circulation in the deep or open Gulf of Mexico, and considers how these features might interact with shelf circulations in the western Gulf. In general, there are minimal discussions of any kind of instrumental methodology in this review. Considerable attention will be devoted to how numerical model results relate to the database. In Chapter 1, some numerical model results were mentioned briefly, and in Chapters 2 and 4 and Appendix C there is considerable discussion of the intercomparison of observation and model results, with some emphasis on grid resolution and sub-grid-scale parameterizations and boundary conditions. In Chapter 1 the reader was exposed to most of the physical processes that will be encountered throughout Volume I. Chapter 2 is to a large extent devoted to a more detailed examination of the Loop Current and its Eddy Field (which may be collectively referred to as the Loop Current System or Loop Current Regime). The contemporary observational view is of a very active GOM that is densely populated with interacting anti-cyclones and cyclones (Berger et al., 1996; Biggs et al., 1996; Fratantoni, 1998; Fratantoni et al, 1998; Hamilton, 1992, 1998; Hamilton et al., 2002; Sturges and Leben, 2000; Zavalla-Hidalgo et al., 2003, this review), with cyclones playing an important role in the final stages of LCR separation [for early examples of this issue, please see Cochrane (1969b, 1972) and Vukovich and Maul (1985). Maul (1977, 1978), and Maul et al. (1985) pioneered the idea that LCR formation is related to an exchange of water between the Gulf and Caribbean. Oey (1996) was the first numerical model application to contain this result, and these types of processes have been recently been elaborated upon observationally by Bunge et al. (2002). Warm-core eddies generated in the Loop Current System also collide with the slope-rise-shelf system in the western Gulf, with cyclonic byproducts, and influence shelf circulations there. In Chapter 3 of Volume I there are discussions of Shelf-Gulf and to some extent Shelf-Shelf interactions. There is also a brief initial introduction to the physical oceanographic characteristics of the LATEX shelf circulation, and to coastal upwelling in the western Gulf. Chapter 4 is a summary of the information and ideas presented both in the appendices and in the body of this review, along with recommendations for future work. A description of a new perspective for the eddy field in the Gulf is a major component of Chapter 4.3 in this review volume.

As indicated by the table of contents, in this review a variety of appendices are used to lay out background information, or as a place for details. Appendix A is a sequential collection of annotated publications on the Physical Oceanography of the Gulf of Mexico. Appendix B is the bibliography, containing citations associated not only with topics covered in Volume I of this review, but also publications useful for comparative studies. The material in Appendices A and B is what I have gone through (read or scanned) in order to familiarize myself with the physical oceanography of the general region in which I have retired. I have found that the papers I read on the Gulf circulation make up a fascinating story. Since this is an exposition directed toward the coastal and deep GOM circulation neophyte, an extensive bibliography is compiled in an Appendix B (one like this will be contained in each volume of this review), and the identification of key references is a priority. More or less all available and relevant publications, of any origin, have either been read or scanned and included in Appendix A and B. Recent bibliographic material may be found in reports compiled by Continental Shelf Associates (2000a, b). The idea is that becoming familiar with the nature and location of the publication base is both good preparation for doing research AND for evaluating "expert" and other opinion(s). Numerical models of the ocean circulation have been formulated and used actively for the last 35 years or so, and are becoming more and more widely used, in more and more ways, in coastal and estuarine regimes as well as the open ocean. Appendix C considers the status of a variety of numerical experiments in diverse domains, as they relate to observation in general terms, but focusing on various features of the large-scale circulation in the GOM. There are suggestions in the publication base that the Gulf of Mexico is most appropriately modeled in an extended domain from the point of view of boundary condition specifications, perhaps even in an Atlantic basin scale configuration. Since this requires some knowledge of how basin scale models relate to the database, these activities are discussed in general terms quite a bit in this review.

This review contains various discussions of what to expect from numerical modeling methodology, oriented primarily toward an audience that is not particularly familiar with the choices that get made, or with how realistic numerical model results might be (or not). The emphasis in Appendix C is on how models relate to the observational base for serious students of this topic, and an appendix on this topic will be a component of each of the volumes of this review, focusing respectively on the deep Gulf and coastal circulations. Appendix D is used to put the general circulation in the Gulf of Mexico into context with respect to the global scale ocean circulation, especially of course, the Atlantic Ocean. That is, Appendix D contains a summary description of the basic characteristics of the Atlantic Ocean circulation patterns and their global linkages in which the Gulf of Mexico (GOM) is embedded (please also see Chapter 4 for a brief summary of this issue). There is an emphasis on the component of the meridional overturning cell (MOC) in the Atlantic Ocean that is associated with the upper ocean replacement flow carried by the Loop Current, in addition to its wind-driven component, the former to provide the upper layer waters needed for the formation of North Atlantic Deep Water (NADW) in the northernmost North Atlantic Ocean. The influence of eddies in the Brazil Current and in the Caribbean Sea (please see Appendix D) is also of concern. My hope is that Appendix D, as well as this review in general, will be seen as an innovative effort to involve the major circulation features of the Gulf of Mexico in the mainstream of research on current systems throughout the World's Oceans. Appendix D also contains a discussion of some of the general concepts and practices used in the physical oceanographic community for the reader who is not familiar with this field.

Acknowledgements are in Appendix E. Chapters and Appendices and their sections are designed to be somewhat independent.

Volume II of this review will examine in some detail coastal circulations and their interactions with the open Gulf and with adjacent shelf circulations. In analogy to Volume I, there will be in Volume II an appendix containing an extensive literature review on shelf circulations, and an appendix on coastal model results. Volume II will consider geographically each of the shelf regimes identified in Figure 1-2 in varying detail, depending on the information available. In addition to local wind and buoyancy forcing, estuaries respond in co-oscillation modes to forcing from the innermost shelf in the vicinity of inlet entrances. The discharge from inlet channels may also affect coastal circulations, the most prominent example in the Gulf of Mexico being the influence of the discharge from the Mississippi River System. Coastal sea level is influenced by both shelf specific and Gulf scale processes, and these are discussed primarily in Volume II. In Volume I, coastal sea level is discussed occasionally in Chapters 1 and 3 mostly. For example, a pronounced summer minimum in coastal sea-level in the western Gulf is attributed initially to the relaxation of the downwelling regime on the shelf in the westernmost Gulf during the non-summer months in May-June, followed later in the summer by seasonal modifications to the stratification on the shelves and with upwelling (both wind and eddy driven) prior to the spinup of the downwelling regime in September-October. Key references on coastal sea-level around the GOM are Marmer (1954), Whitaker (1971), Blaha and Sturges (1978, 1981), and Sturges (1993).

END OF SECTION 3, AND OF CHAPTER 1, LAST UPDATED 22 NOVEMBER 2003.