REMOTE SENSING STUDIES OF THE GULF OF MEXICO - AN EFFORT IN RED TIDE PREDICTION

A Report

to

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INTRODUCTION

Red tides are natural phenomena reported around the world and described as higher than normal concentrations of microscopic algae. They appear as discoloration of water, and are known to cause fish kills and temporary respiratory irritation in humans. Their presence in an area usually impacts both the fishing and recreation industries. The organism associated with red tides in the Gulf of Mexico is *Karina breve spp* (previously known as *Gymnodinium breve*). This organism is reported to have a resident population here and, to be transported throughout the Gulf by the Loop Current (LC) (Tester et al., 1993 and Tester and Steidinger, 1997). In the Texas coasts, blooms of this organism are not as predictable or as frequent as those in Florida Gulf coast. At least, that is the perception that the community has. Texas Parks and Wildlife (TPW) reports that red tides blooms occur in the western Gulf between Galveston Bay and Port Arthur, and south to Tampico, Mexico (Figure 1.).

The appearance of the blooms in the Gulf of Mexico has been associated with various environmental parameters such as bottom temperature and proximity to the thermocline (Tester and Steidenger, 1997), winds (Culver et al., 2000), and sea surface temperature (SST) (Stump et al., 1998). These associations are made in an effort to investigate the causes of the blooms, the location of the seed pool, and the possible development of a forecasting system based on environmental conditions favoring bloom conditions. Although blooms occur mostly in late summer and early fall, there are blooms that occur in Florida at other times of the year. In Texas the large blooms appear in those months, but not every year. Their magnitude and specific site of impact vary, as well. In general, red tide blooms seem to occur in the presence of calm winds, and warm temperatures, which are the prevalent conditions in the summer and in early fall in the Gulf of Mexico.

SATELLITE DATA IN THE STUDY OF RED TIDES

Although satellites provide synchronous views of the earth's processes, and are excellent tools for near-real time monitoring, they are not without problems when their data are used for forecasting purposes. Sensors with visible and infrared bands suffer from blackouts of data due to the presence of clouds. Clouds are more prevalent in the summertime and in the presence of wet atmospheric conditions such as those occurring in the Gulf of Mexico prior to or at the time of the blooms initiation. When clouds block the view of earth surface, they create large voids of data that do not usually occur at equally spaced intervals. This makes the time-series analysis of satellite imagery difficult because of the additional work and modeling required to mask the clouds in the imagery and reconstruct the data under them (Gallegos et al., 1994; Lee et al., 1995). Beside the loss of data, clouds contribute to erroneous estimations of sea surface temperature in the imagery. Although it is easy to identify the cold and high clouds for their high albedoes, it is nearly impossible to separate the low level-cloud albedoes from the temperatures in the ocean. In the summer time in the Gulf of Mexico, the low-level cloud problem is compounded by surface heating which renders AVHRR IR bands almost useless. Although the large gradients in temperature, such as those of the edge of the LC and eddies are still discernible throughout the year, the estimation of the absolute SST in general is not reliable in the summer. Studies linking SST and bloom occurrences have been more successful when attempted at other times of the year (Stumpf, 1998).

SeaWiFS, the ocean color sensor launched by NASA in 1997 to replace CZCS, produces highly useful data, but it has its share of problems inherent to all passive sensors, which view the spectrum in the visible bands. SeaWiFS is unable to identify the spectral signatures of the in-water particulate components such as phytoplankton, detritus, and minerals from coastal areas. It is impossible to spectrally separate the red tide signature from the sediment signature using data from this satellite because their signatures overlap in the blue region of the spectrum used for ocean color determination. A red tide signature is usually identified and tracked after reports of discolorations or fish kills have occurred, not before. For a system to be useful in forecasting work, it needs to be able to identify a given signature prior to the occurrence. SeaWiFS is useful in verifying findings from other data or from modeling efforts.

A system that has not been fully exploited but that has potential in environmental monitoring is ERS-n. Although its coverage is limited, its footprint coarse (34 Km) and its acquisitions in coastal waters not very because they contain tidal effects, it does not suffer from the cloud problem, or surface heating. Altimetry data monitor changes in the surface slopes throughout the year. Features such as the location of the LC and eddies are easy to identify by their surface slopes. Comparisons of the surface slopes and SST temperatures in the Gulf of Mexico revealed highly accurate matches between these two parameters (Lillibridge et al., 1997). In this report, we examine two satellite products obtained from AVHRR and blended T/P-ERS-2 data, and evaluate their usefulness in predicting environmental conditions leading to red tide occurrences in the Texas coast and the Gulf of Mexico, in general.

MATERIALS AND METHODS

For this investigation, we used 2,392 Regional Frontal Analyses (RFA) of the LC and associated eddies obtained from Naval archives and 305 blended T/P and ERS-2 sea surface height anomaly minus model mean products from the University of Colorado – Center for Astrodynamics.

In the RFA, identification of ocean features is accomplished by defining the surface position of fronts and eddies through daily analysis of near real-time AVHRR infrared and visual imagery obtained from NOAA polar orbiting satellites. Multi-channel sea surface temperature algorithms are used to create images in 256 gray shades, which are optimally enhanced to locate ocean thermal features on cloud-free areas. Fronts and eddies are then digitized on the satellite image to include frontal positions (latitude/longitude) and frontal strengths by temperature gradient (degree C per 10 nautical miles). Satellite altimeter sea surface height data is used to locate western boundary current fronts and eddies in cloud-covered regions. These contain geographical location and temperature of the LC at the time of the satellite pass (Figure 2). Eddies are identified by the location of the center of the eddy, the temperature at that location, and the lengths of its maximum and minimum axes.

Mean locations of the LC were computed from the RFA. The daily LC position is represented by 40 to 60 geographical locations (latitudes/longitudes). They start at the Yucatan channel, where the LC enters the Gulf and end at the Straits of Florida where the LC exists the Gulf. A line connecting these points indicates the position of the LC in a given day. To obtain monthly averages of the LC position, this line is divided into a number of segments of equal length. The corresponding endpoints of each day are then averaged. A new mean plot is generated for each month and set aside for further comparisons (Figure 2)

To compute the monthly probability of LC position, the entire Gulf of Mexico region from 20 ° N to 30 ° N, and from 79 ° W to 91 ° W, was divided into 1080 segments of 1/3° by 1/3 °. Every time the LC crossed one of the segments, it was counted as one occurrence. The probability of occurrence is then the number of times the LC crossed a segment divided by the number of days with data. The higher the probability, the longer the LC stayed at that specific geographical location.

To determine how far the LC penetrated into the western Gulf of Mexico and over the continental shelf of Florida, two grid systems were developed (Figure 3a and 3b). The number of grid points crossed by the LC was labeled the "distance of intrusion". The number of grid points crossed by the LC per month was labeled the "frequency of intrusion". A third grid system (Figure 3c) was used to monitor the location of eddies in the western Gulf and the intrusion of the offshore waters onto the Texas-Louisiana continental shelf in the altimetry data

The altimetry data was created by the Center for Astrodynamics of the University of Colorado in association with NOAA. Lillibridge et al. (1997) describe the processing of these data. For the data to be useful in our analysis, yearly means were removed from the blended T/P and ERS-2 sea surface height anomaly products. We followed the 0-cm isopleth as it meandered. When it crossed the continental shelf, it created an area enclosed by the meander and the edge of the continental shelf. The number of grid points covered by this area, are measures of the daily offshore water mass intrusion (area of intrusion). The altimetry analyses were limited to the years 1998 and 2000 and to the western Gulf. The combination of the SST and SSH data were crucial to our understanding of the movement and interactions of the water masses in the eastern Gulf.

It would have been ideal to compare red tide blooms *in situ* locations to the geographical locations and times in which the satellite data indicated the presence of a meander with "high probability of occurrence" off the coast. However, gathering of the available data from the various agencies, and formatting the data to match our database, was a major effort beyond the scope of this investigation. We utilized descriptive information on red tide occurrences along the coast of Texas provided by Dave Buzan of the TPW to verify the approximate location of the blooms in the western Gulf, exclusively. Data from 1998 and 2000 were used to demonstrate the behavior of the LC and the position of 0-cm isopleths of the altimetry data in a year in which there was no red tide reported and one in which there was a major red tide occurrence in the Texas coast.

RESULTS

A. Regional Frontal Analysis

Our results were based on observations of the daily RFA, mean location of the LC, the results of the grid analysis, and the monthly probability of occurrence computations from 1993 to 2000. These are summarized in Figure 4 for the Eastern Gulf and Figure 5 for the western Gulf. Monthly descriptive observations are presented below.

1. Eastern Gulf

For the eastern Gulf, we looked at the location of the LC with respect to the continental shelf of Florida, and noted the geographical areas covered by the meanders when they intruded the shelf. We also monitored the formation of eddy-like features that form in the northeastern Gulf in some years. Of particular interest were times in which the LC flowed away from the coast, and those in which it flowed on top of the continental shelf.

1993, was characterized by the flowing of the LC very close to the Florida continental. Although it did not have large and extensive intrusions into the shelf, it did not completely leave the edge of the continental shelf for long periods of time. During the fall months, it even appeared to be hugging the 200-m isobath. These minimal intrusions were observed in April between 25° N and 27° N, and in May at 25° N. From June to November, the LC never left the edge of the continental shelf of Florida. Hence, the high probability of intrusion observed in Figure 7 during this time. In November and December, intrusions were observed from 24.5 ° N to 27 ° N.

In **1994**, there were intrusions along the eastern continental shelf of the Gulf of Mexico from 24.3° N to 28° N from January to March. In April and May, the intrusions occurred below 26° N, exclusively. There were some intrusions from June to September. There were intrusions in October and November. In December, the LC retreated into the Gulf.

In **1995**, the LC appeared closer to the continental shelf of the eastern Gulf than in the previous year. It had large intrusions in March and April between 25 ° N and 28 ° N. In March a large eddy-like feature was observed in the northeastern Gulf that appeared to be entrapped in the 200-m isobath in front of the Mississippi-Alabama coast. In that same month another intrusion was observed on the eastern continental shelf between 24.5 ° N and 26° N. In April, a hook-like jet extended into the western Gulf to 90.5°W. In May, the intrusions extended along the Florida continental shelf from 25 ° N south to 29.5 ° N.

In June and July, there were very small intrusions but in August, September and October, large intrusions were observed first in an area between 24° N and 27 ° N, and then extended from 25° N to 29° N. There were no noticeable intrusions during November and December.

1996 was an especially active year for intrusions. The LC invaded the continental shelf of Florida with large intrusions from January to December. Intrusions occurred from 24.5 ° N to 28 ° N from January to July. The largest intrusions of this entire study occurred in October, November and December. In these months, the eastern half of the LC appeared to be flowing over and in the center of the Florida continental shelf. The left half was observed at the edge of the continental shelf.

1997 was a fairly uneventful year for the Florida shelf. Except for some small intrusions, which occurred from February through May from 24.5° N to 27° N, and in June and October below 26° N, the LC was seen flowing, but not intruding, along the 200-m isobath.

1998 resembled very much 1996 in that it was a year of many intrusions. However, These intrusions did not penetrate into the continental shelf as much as those from 1996. We observed significant intrusions from February to April. The intrusions with the higher frequency of occurrence (> 0.6) (Figure 6) of this year were observed in the northeastern Gulf from August to November. Eddy-like features were observed over the continental shelf in October

1999 was a year in which intrusions occurred in January and continued until April from 24°.6 N to 28.2° N. We were unable to analyze the data from May through August because the regional analyses were unavailable. Intrusions were again observed from 24.5° N to 26.2° N in November, but these were rather small. The LC remained away from the continental shelf during September and October.

2000 is a year in which we only analyze data from January to August. In this year, there were intrusions in every one of months examined. The intrusions occurred along the Florida shelf from 24° N to 29° N. Eddy-like features were observed in March at 28° N, 86 ° W. The highest intrusions with the highest probabilities (≥ 0.6) (Figure 7) were observed in June. In this month, the LC invaded the continental shelf and a large eddy was clearly observed to be spinning into the shelf. Its center was located at 28 ° N, 86 ° W

2. <u>Western Gulf</u>

The analyses for the western Gulf consisted of tracking the location of the displacements of the LC occurrences into the western Gulf. We also identified those months in which there were indications of eddy formations in the western and eastern boundary of the LC, and those months in which eddy-like features crossed the 200-m isobath off the Louisiana-Mississippi coast.

In **1993,** the largest displacements of the LC towards the west occurred in March to May. The largest of these occurred in May when LC isotherms reached as far west as 89.8° W. In June an eddy-like structure was observed in the central Gulf from 24° N to 28.5° N. The smallest displacements towards the west occurred from September to November.

In **1994**, the largest displacements occurred in July to September. These ranged from 89.8° W to 90.2° W. The smallest displacements occurred from October to December (87.4° W to 88° W). This year had many eddy-like features, which were observed to protrude from the LC towards the west in February, March, and July. In March, April, and August to October, the protrusions moved to the north between 27° N and 28 ° N. In August to October, these were observed closer to the 200-m isobath and in September and October they crossed the edge of the continental shelf to the west of the Mississippi delta. The September and October eddy-like features extended from 25° N to 28.5° N. In this year two small eddy-like features were observed in the eastern Gulf between 25° N and 29 ° N in March and between 25 ° N and 27.5 ° N in June.

1995 was a rather peculiar year because the LC 1) had large displacements to the west, the largest of which occurred in February, March and August, and 2) spawned six eddy-like features in the eastern Gulf but none in the western Gulf. The eddy-like features were observed in March to May and August and September. These features intruded the Florida continental shelf.

1996 had two major displacements of the LC towards the west. The first of these occurred in March and the second from September to October (90.1 ° W). Two eddy like features were observed in September between 22.5 ° N and 26° N and in October between 23 ° N and 27.6 ° N. In this year, the LC was observed to be displacing to the north and appeared to form an eddy-like feature that intruded the 200-m isobath west of the Mississippi delta between 28.2 ° N and 29.5 ° N, and 88.8 ° W and 90.1 ° W. In February, an eddy-like feature was observed in the eastern Gulf in February, which extended from 25.5 ° N to 28.5 ° N along the 200-m isobath in the Florida shelf.

1997 was uneventful from Jan to May. In June the LC generated an eddy-like feature between 25 ° N and 27 ° N and 88 ° W and 90.1 ° W. In October, a large displacement of the LC and what appeared to be a large eddy-like feature intruded the continental shelf of the northern gulf west of the Mississippi delta at 28.7 ° N and 89.2 ° W. This feature, in contrast to the other features that impacted the northern gulf, was completely displaced to the east.

1998 was very different from all the years studied, not only because the LC had the least variability of all the years studied, it also stayed in the eastern Gulf close to Florida all year long. The only time the LC crossed 90° W and spawned an eddy-like feature between 22.7 N and 25.8 ° N, was in October. Another peculiarity of this year is that the LC remained south of 26 ° N from March to September, entering the Gulf only in January, February and October.

1999 was difficult to analyze because of a large data gap that occurred in the RFA database from May to August. In the first four months, the LC flowed east of 89 ° W. In March, it displaced north towards the Louisiana coast west of the Mississippi delta, but did not cross the 200-m isobath. In September, it spawned a large eddy-like feature that continued into October, but crossed the 200-m isobath only 2 days. The only significant western intrusion occurred in November when a finger-like feature spawned from the LC and extended from 87 ° W to 89.9 ° W along 25 ° N.

In **2000** we only analyzed data from January to August because the digitization of the LC and eddies was not complete. The LC was observed to be leaning towards the western Gulf in January, April and May. This year also was characterized for having many small intrusions into the western Gulf. Insignificant meanders occurred in February to April between 26 ° N and 27.8 ° N. In February, there were two short-lived intrusions (low probability of occurrence). One occurred over the Yucatan continental shelf between 22 ° N and 23.8 ° N and, the other between 24 ° N and 26.5 ° N. In March an intrusion was observed between 26 ° N and 27.8 ° N. In April, the intrusion was reduced to a finger-like projection between 25.7 ° N and 26.7 ° N. In May, an eddy-like feature was formed between 25 ° N and 27.5 ° N. In June, the LC split into two major lobes. One of them became a large meander that intruded into the western Gulf, crossed the north Yucatan continental shelf and reached 89.1 ° W. The other became an eddy-like feature with a center located at 28 ° N, 86 ° W that moved onto the Florida shelf and remained there for most of the month of June. The Yucatan eddy was not registered in our plots because it was off the grid system and was only identified from visual inspection of the mean plots. It extended from approximately 25 ° N to 29 ° N. In July and August the LC into the Gulf and remained below 26 ° N.

B. Altimetry data

The T/P-ERS-2 blended products minus the mean were very useful in helping us understand the interaction of the waters masses in the western Gulf. We used 350 of these products to trace the movement of the LC eddies into the western Gulf and to monitor the intrusion of the offshore water onto the continental shelf from April to September of 1998 and 2000. This was done in an effort to quantify the behavior of the water masses during a year in which no red tide was reported in Texas and one in which a major red tide occurred. We used as a point of reference the 0 cm-isopleth and followed it through the summer and into the fall of both years. Inspection of the altimetry products, indicate that in 1998 (Figure 8a), the 0-cm isobath remained below latitude 28°N for the entire summer and fall and never approached the edge of the continental shelf. Conversely, in the altimetry products from 2000 (Figure 8b), the 0-cm isopleth was observed to extend and form meanders into the continental to the east of Sabine Pass and off Brownsville. In the year 2000, the 0-cm isobath extended as far north as latitude 29° N, and as far west as 97.2 ° W. Closer inspection of the imagery indicated that it met –10 cm isopleth, which may be associated with the edge of the plume from the Sabine River. However, when analyzing altimetry data over shallow waters such as those of the continental shelf, one must proceed with caution because the data may include tidal effects. These effects may result in errors between 5-10 cm. The orbital models used in the processing of the altimetry data are not always able to remove this contribution as they do in open waters, where the error is 1-2 cm. Our goal is not to use these data to quantify absolute SSH, but rather to compare the patterns from one year with those of a different year, assuming that the same level of error exists in both data sets. The number of grid points in the areas that intruded into the coast were determined and plotted with respect to time. Figure 9 is a comparison of the areas crossed by the 0-cm isopleth in the Texas-Louisiana during the summer and early fall of 1998 and 2000. This graph clearly indicates that the intrusion of the offshore waters in the Texas coast was much higher throughout these moths in 2000 than in 1998. In addition, a very high peak of intrusion occurred at the beginning of June and ended in mid July. This is precisely the time when the red tide blooms were first reported from the Sabine River area by TPW in 2000.

C. SeaWiFS data

After the red tides were initially reported from Texas in June 2000, we acquired imagery from SeaWiFS from June to September of 2000. The data were purchased by NMFS and processed at NRL laboratory at Stennis Space Center in Mississippi. In the images, the red tide blooms appear as streaks of high chlorophyll concentrations on the continental shelf to the east of the Sabine Pass. The streaks were very clear on the August 17 image (Figure 10a). A subsequent image from September 18 (Figure 10b) shows the red tide to have extended further south along the Texas coast. The imagery match the description of the locations reported by TPW. Both the SeaWiFS imagery and the TPW descriptions of the red tide occurrence along the coast of Texas were used to verify the location and time of the red tide occurrences indicated by our the computations of frequency of occurrence in the altimetry data sets.

DISCUSSION

During the time of our observations, the eastern Gulf experienced three years of fairly low activity. These were 1993, 1994 and 1997. These years were characterized by small intrusions onto the continental shelf below 27 ° N, and by the LC flowing close to the shelf for most of the year. 1995 saw an increase in the formation of eddy-like intrusions along the 200-m isobath of the west Florida coast and in the northeastern Gulf. There were six eddy-like features formed during this year. These occurred in March to May and August and September. 1996 and 1998 had extremely high activity. 1996 was especially active year for intrusions. In these years, the LC not only produced a myriad of intrusions, it actually appeared to be flowing inside the shelf for long periods of time. 1999 was a year, which we could not fully analyze for lack of data from May to August. We analyzed the remaining months. These data revealed that the largest fluctuations and intrusions occurred in April and the activity was concentrated mostly between 24.6 ° N and 28.2 ° N. In the fall, the activity was much smaller and concentrated mostly from 24.5 ° N to 26.2 ° N. Our data indicated that in the year 2000, the LC had many intrusions and an eddy, which appeared to linger for a while inside the Florida shelf.

There were highly active periods in the western Gulf in 1994, 1997 and 1999. In 1994 the LC was highly active and produced many meanders, which may have contributed to the generation of nine eddy-like features in the western Gulf. In 1995, all the LC activity was concentrated in the eastern Gulf, where six eddies were shed. In the western Gulf, the eddies shed in 1994 were present. We assumed that 1995 would be a year of extensive red tides in the western Gulf. To our surprise, the TPW reported only a weak red tide (<601 cell/ml) in the lower Laguna Madre along the north shore of port Isabel in September 1995. This led us to speculate that because the LC was busy shedding eddies in the eastern Gulf, there was not enough forcing in the western Gulf to push the eddies against the continental shelf and produce the conditions necessary to enhance red tide production.

In 1996, an eddy-like feature was generated off the LC. It impacted the Louisiana coast west of the Mississippi delta in March of this year. Cell concentrations of >48,000 cells/ml were reported to occur in the Brazos-Santiago Pass, South Padre island, and Lower Laguna Madre in October and November of this year. It is possible that the eddy-like feature, which was observed in March, may have triggered the red tide blooms of the fall of this year. This assessment may not be so far fetched if we consider that eddies in the Gulf of Mexico have an average speed of 5 km /day and decrease to about 55% of its initial size in approximately 150 days (Vukovich and Crissman, 1986). In 1997, TPW reported red tide blooms from north of Port Mansfield south into Mexico, including Laguna Madre, the Brownsville ship channel and Port Mansfield. We think that these blooms may have been the result of two eddies that occurred in September and October 1996.

The western Gulf experienced the lowest activity of all the years studied in 1998. This was also the year that TPW indicated there were no red tide reports. In this year, the LC was observed to stay at the entrance of the Gulf south of 27° N for long periods of time. When it moved into the Gulf, it was closer to the Florida continental shelf and hugging the 200-m isobath. There were no excursions of the LC towards the west beyond 87° W for most of the year. Only in October, a large meander, which may have turned into an eddy-like feature, was observed on the western wall of the LC. By November and to the end of the year, the LC was observed flowing south of 26° N. In 1999, there were reports of blooms from South Padre Island to Mexico. Since 1998 was an extremely inactive year, the only feature that may have contributed to the 1999 blooms is one that was shed in October 1998 from the central western portion of the LC. In 2000, there was a massive red tide that started in the lower coast in late June and in the upper coast in mid July. We think that the eddy that impacted the northern Gulf of Mexico at the 200-m isobath in September 1999 may be responsible for enhancing the environmental conditions, which led to the bloom of the upper coast. The bloom in the lower coast may have been the result of an eddy that was observed to spawn out of the loop in October and November 1999.

CONCLUSIONS AND RECOMMENDATIONS

Results from the analyses of the RFA and the monthly probability studies indicate the mean position of the LC varies from year to year. In some years there is high LC activity (eddy-shedding and intrusions) and in others there is very little. These fluctuations may play an important role in generating propitious conditions for red tide occurrences in the Gulf of Mexico. If these could be quantified, it is possible that the place, time, and strength of red tide occurrences can be predicted for the western Gulf.

Our data indicated there are two environmental conditions necessary for a red tide to occur in the western Gulf. 1) The LC axis needs to be oriented towards the west , and 2) the eddies in the western Gulf must be shed in the fall of the previous year or at the beginning of the current year. If the axis of the LC lies in the eastern Gulf, and there is little activity of the LC in that year, it is highly unlikely that the western Gulf may experience a red tide in that year. There was an absence of red tide in 1998 when these conditions were present. If there are eddies present in the western Gulf which were shed in the fall of the previous year, but the LC is actively shedding eddies in the eastern Gulf, there is a high probability the red tide of the western Gulf (if it occurs at all) be small and weak, as was observed in 1995.

The displacements of the LC in the eastern Gulf seem to influence the red tide occurrences in the western Gulf. 1998 was a very active year in the Florida shelf. In fact, it was the second most active of all the years studied. It would have most likely produced huge blooms in Florida (which cannot be confirmed for lack of *in situ* red tide data at the time of this writing). However, in Texas, this was a quiet year in which there were no blooms reported

Altimetry data derived from ERS-2 are excellent tools to trace eddy-like features and increases in SSH during the entire year. They do not suffer from the problems inherent to visible and infrared sensors. However, for the data to be useful as a predictor of red tides, it is important to 1) understand that there are large errors inherent to acquisitions over the continental shelf, which may affect the estimations of offshore intrusions into the shelf. 2) know that it may be more efficient to use the altimetry data in conjunction with AVHRR data, which details the fluctuations of the LC. As it was apparent from our data, having eddies in the western Gulf does not guarantee that they will get close to the shelf or that they would intrude onto the shelf, an apparent requirement for triggering of the red tide blooms.

We suggest that a red tide in the western Gulf may be forecasted by following these steps: 1) Consult the history of LC fluctuations in the previous year by looking at the orientation of the LC axis. 2) Determine the number and time of production of the eddy-like occurrences in the in the previous year in the western Gulf. 3) Determine the number of eddy-like features in the first three months of the current year. 4) Determine the number of eddies in the eastern Gulf of the current year.

This is a preliminary study and we were fortunate to find data over many years. We have been able to draw some conclusions that may help forecasting efforts in the future. But by no means, the factors cited in our conclusions and recommendations should be interpreted as these being the only factors necessary for red tide prediction. Although the environmental factors we studied may contribute to enhance the development of a bloom, the generation of a red tide is highly dependent on other environmental, biological and chemical factors.

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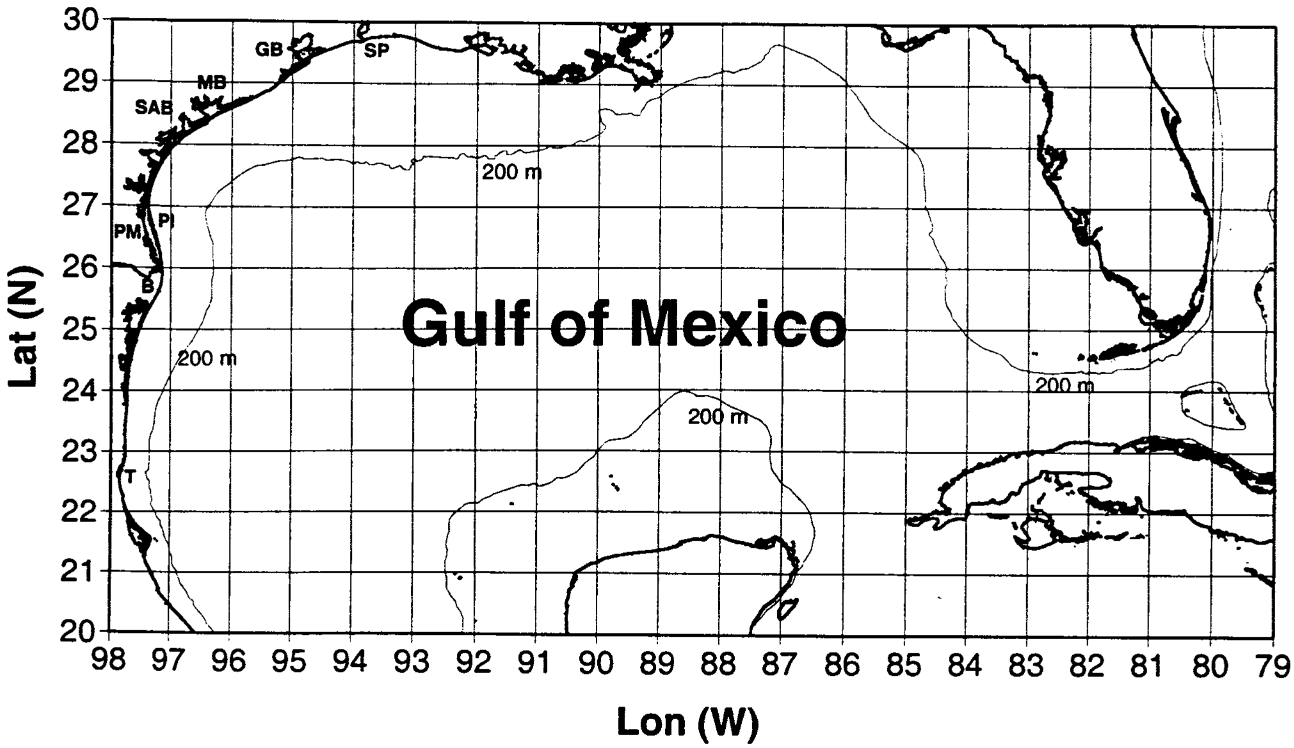


Figure 1. Map of Gulf of Mexico. Geographic names: SP = Sabine Pass; GB = Galveston Bay; MB = Matagorda Bay; SAB = San Antonio Bay; PI = Padre Island; PM = Port Mansfield; B = Brownsville; T = Tampico.

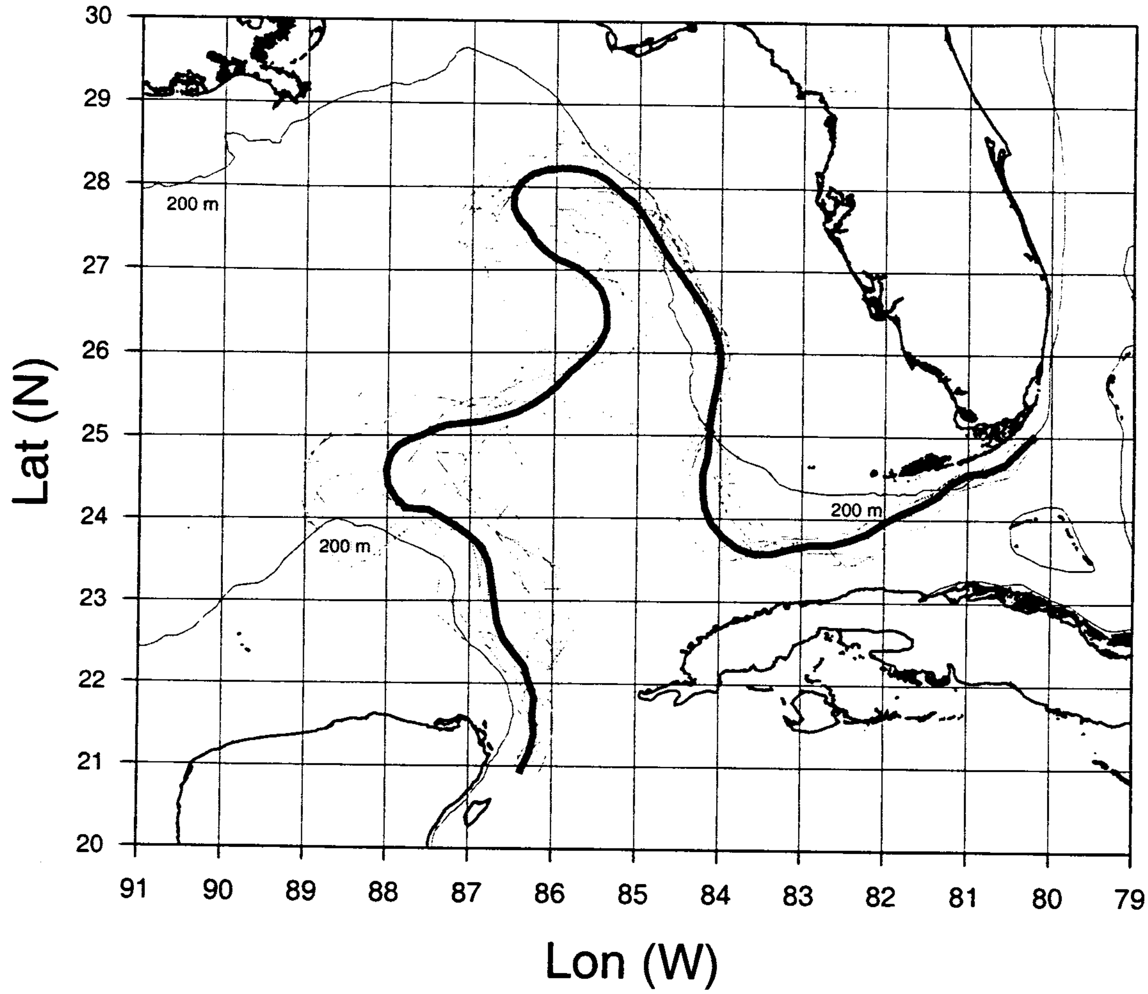


Figure 2. Loop Current position on June 2000. Green lines indicate daily Loop Current positions, and red line indicates monthly mean position.

(a)

(b)

(c)

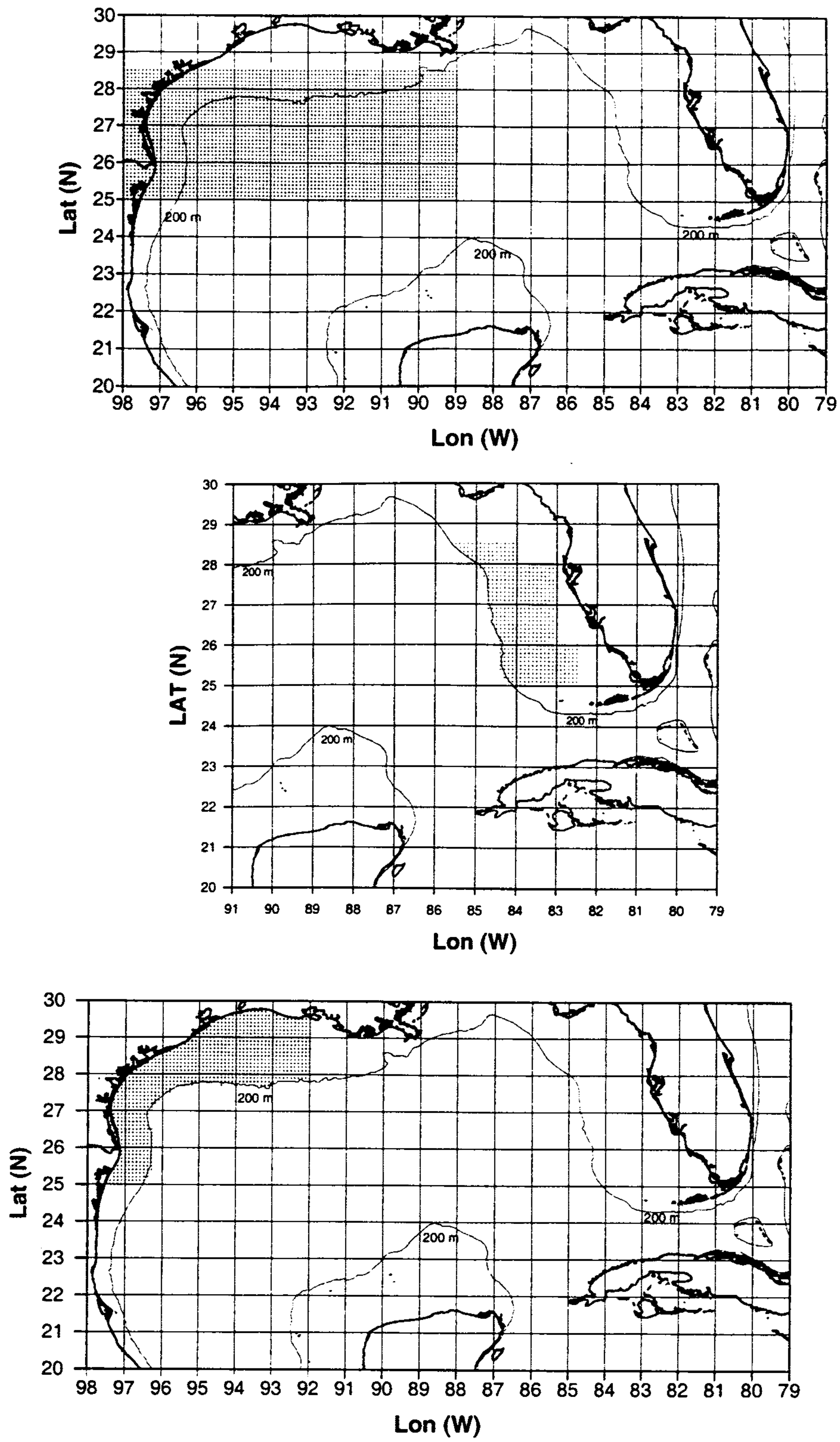


Figure 3. Grid systems for the central western Gulf (a), Florida SW coast (b), and Texas-Louisiana coast.

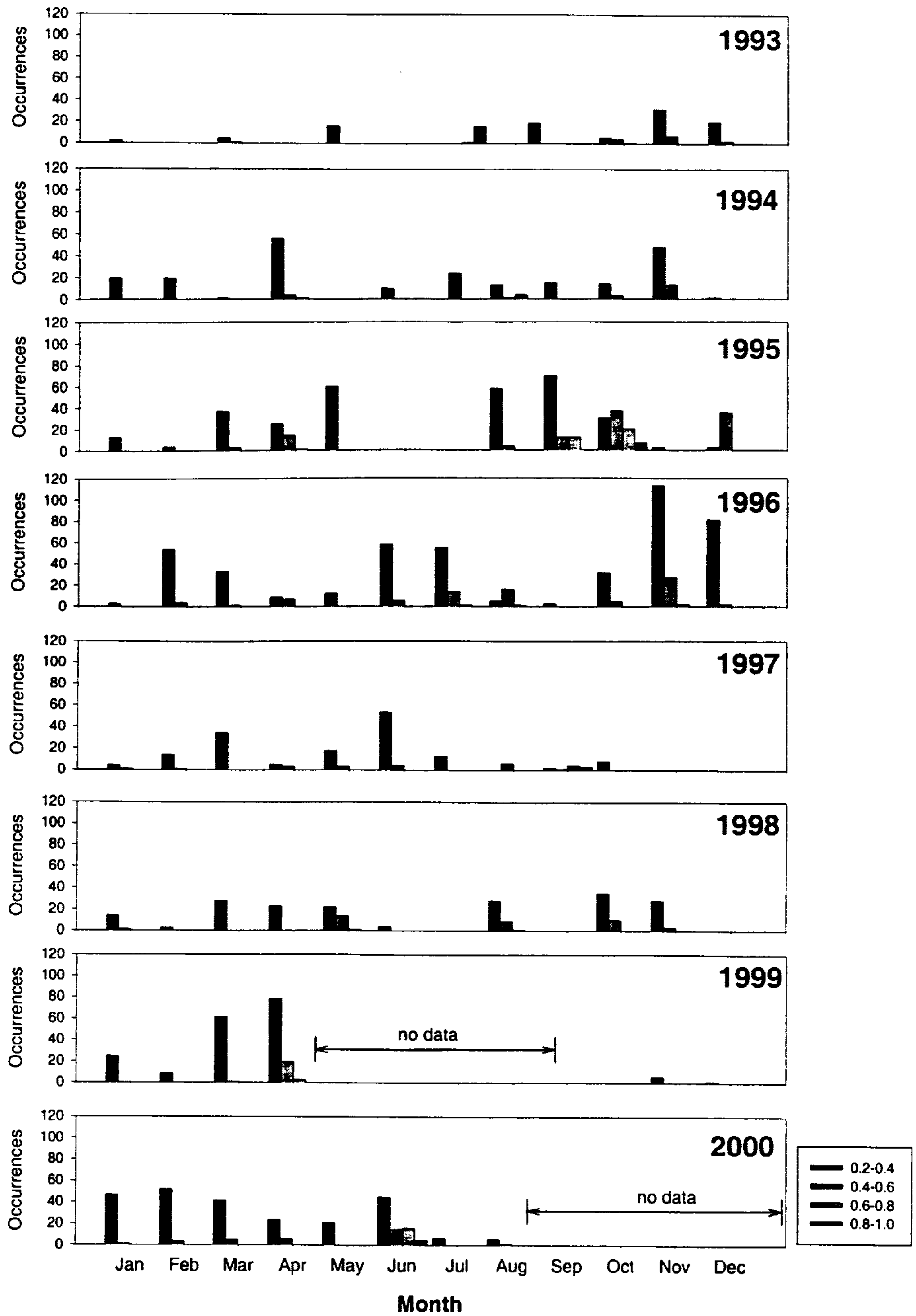


Figure 4. Loop Current occurrences in the eastern Gulf (off SW Florida coast).

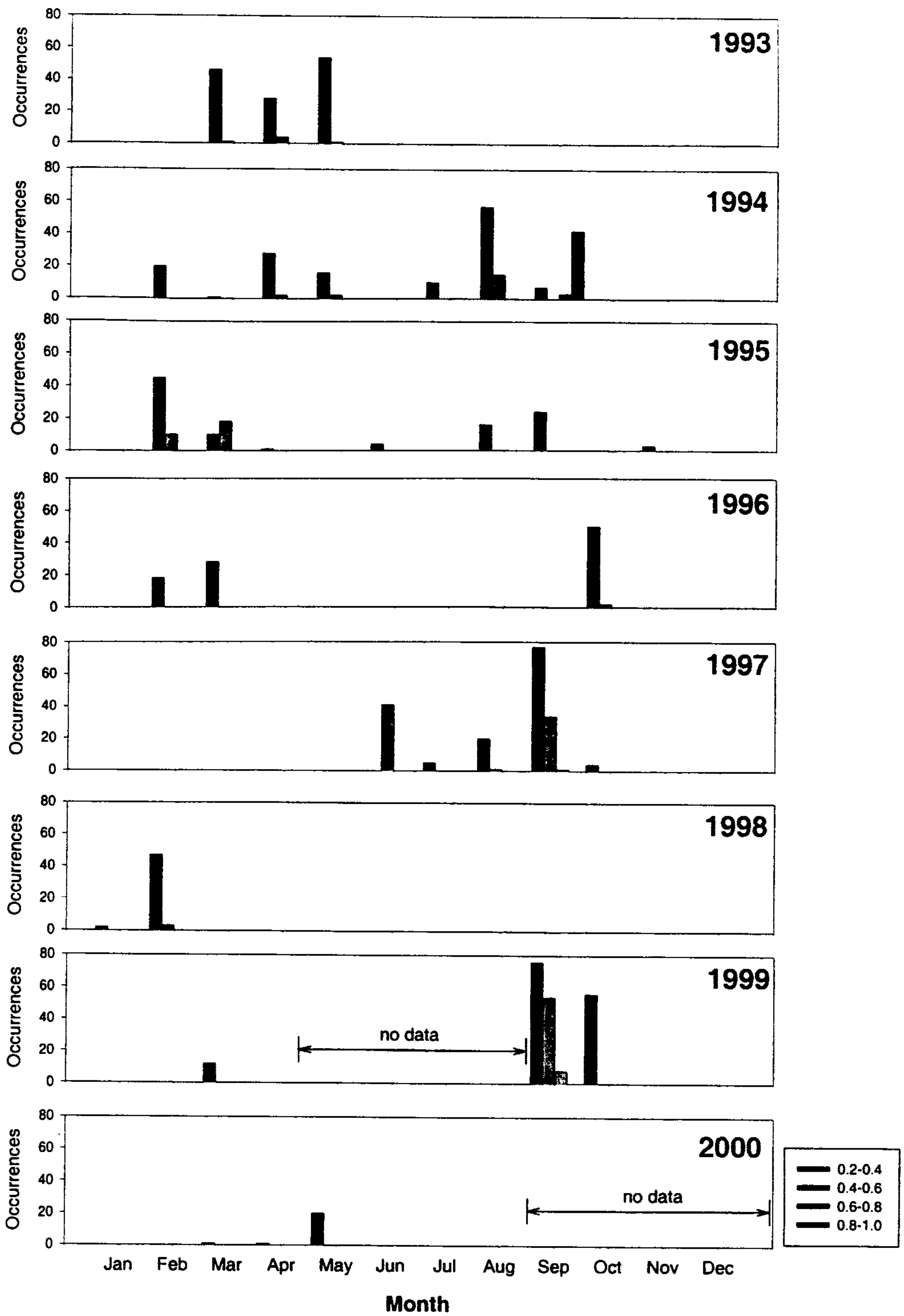


Figure 5. Loop Current occurrences in the central western Gulf.

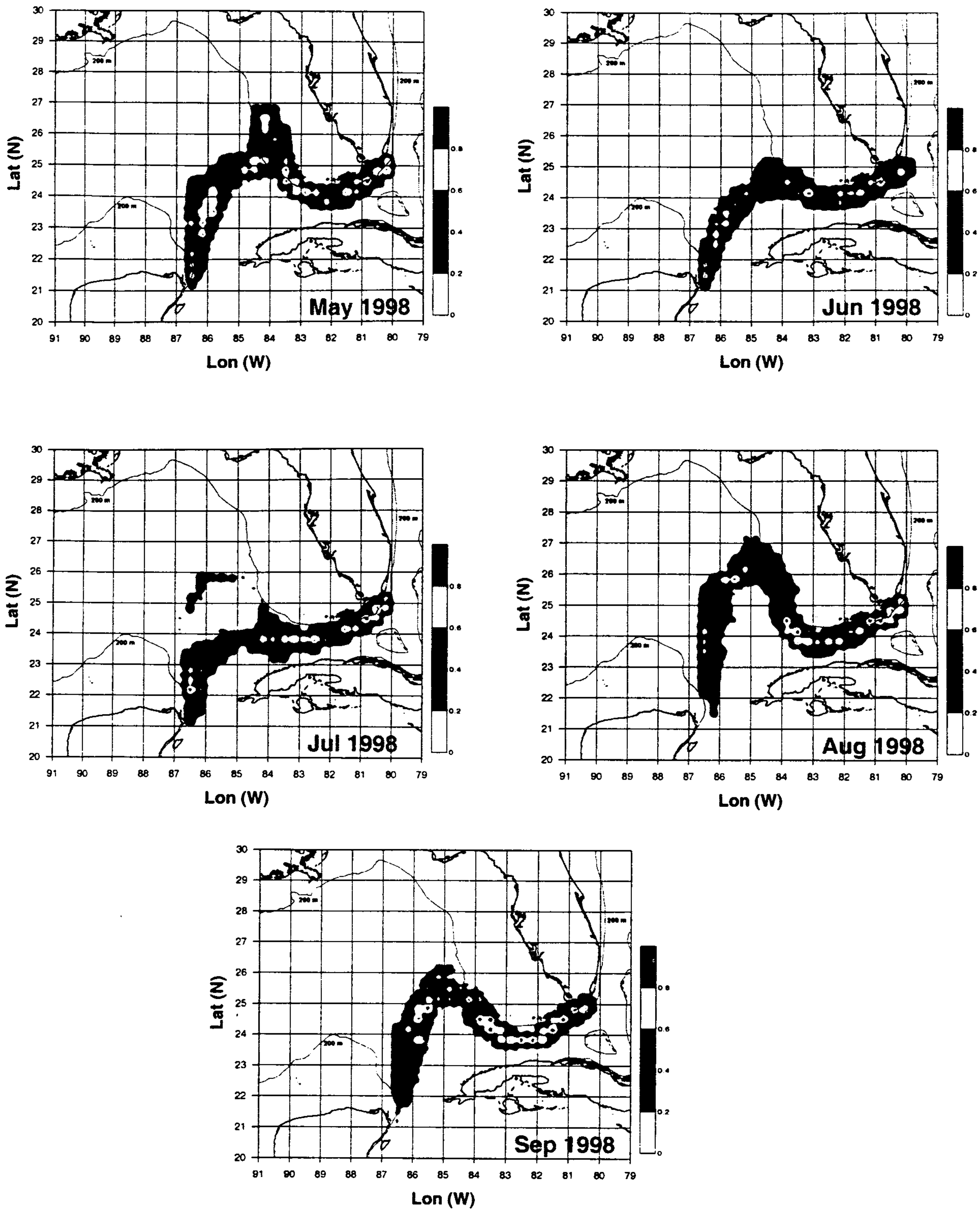


Figure 6. Monthly probabilities contour of Loop Current position, 1998.

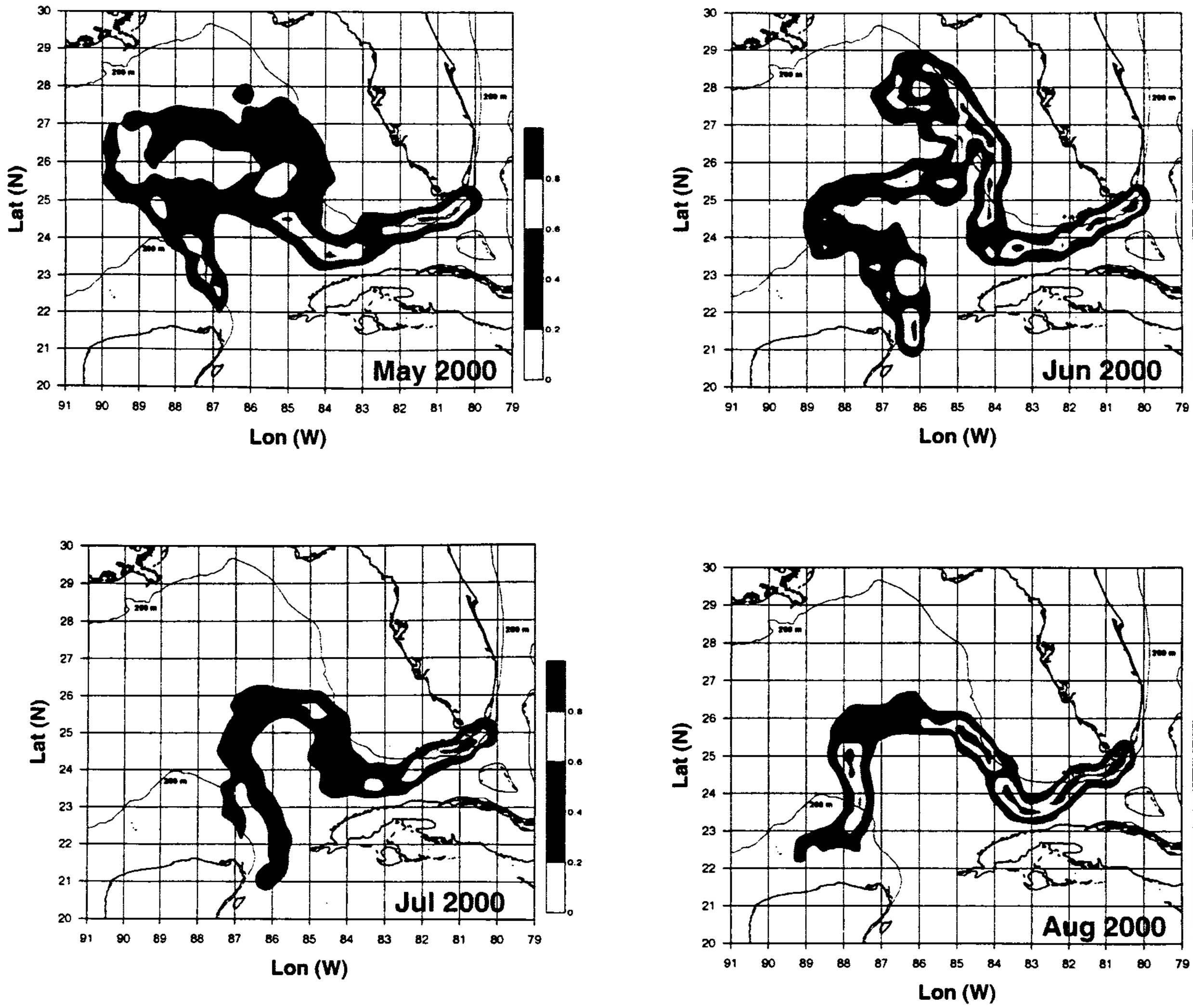
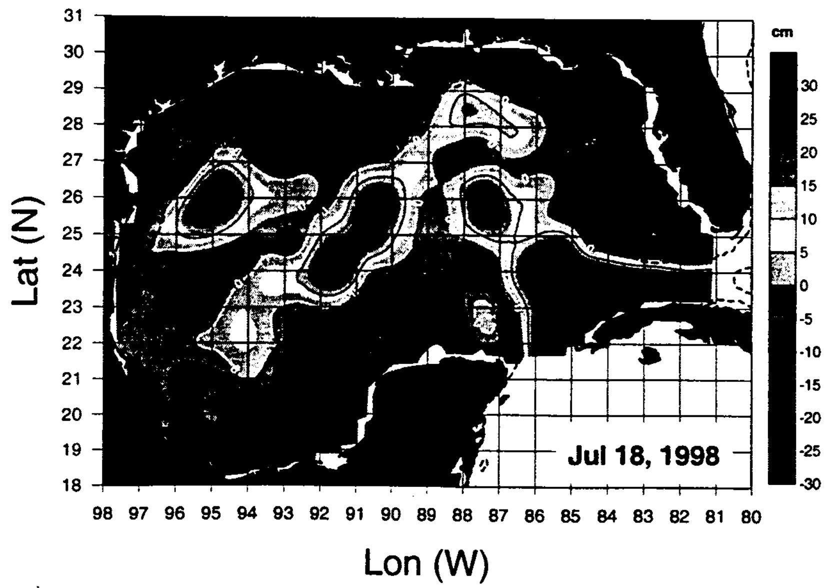


Figure 7. Monthly probabilities contour of Loop Current position, 2000.

(a)



(b)

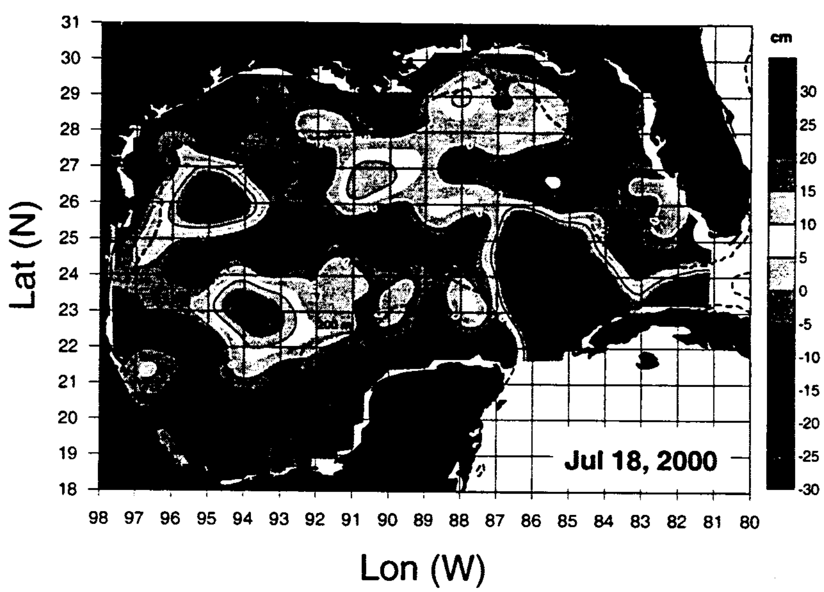


Figure 8. Blended T/P and ERS-2 sea surface height anomaly minus model mean products corresponding to July 18, 1998 (a) and July 18, 2000 (b). White contour lines represent the 0 cm isopleth.

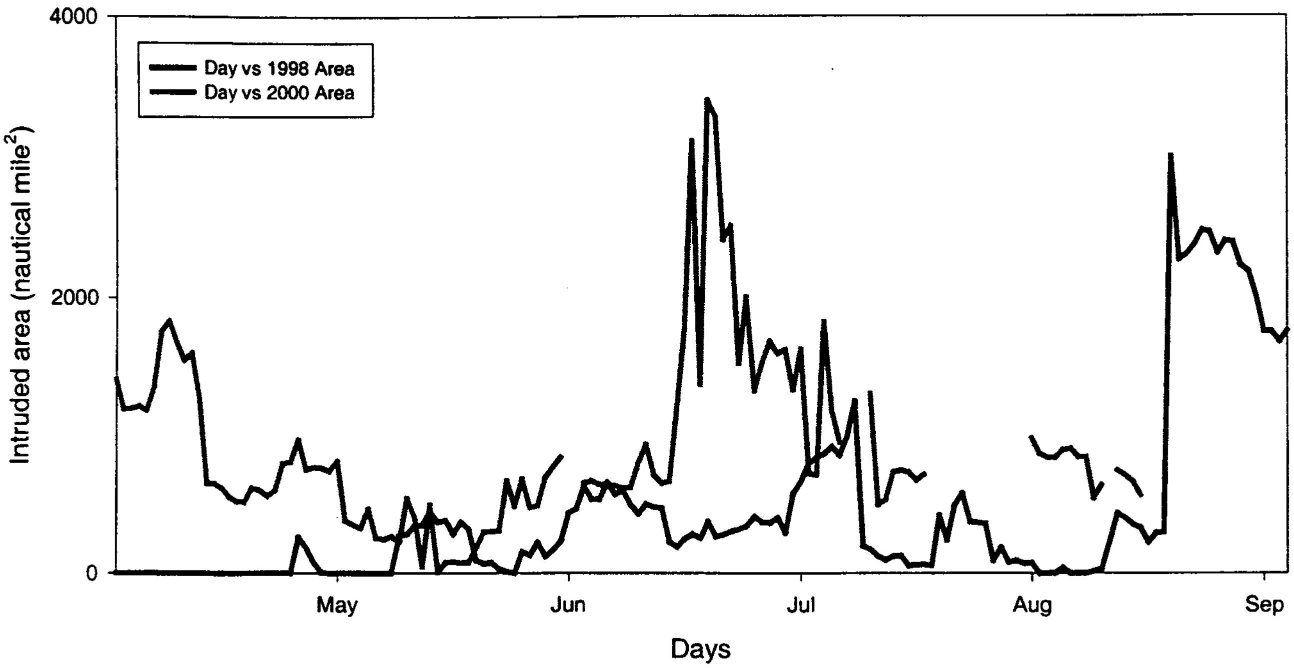
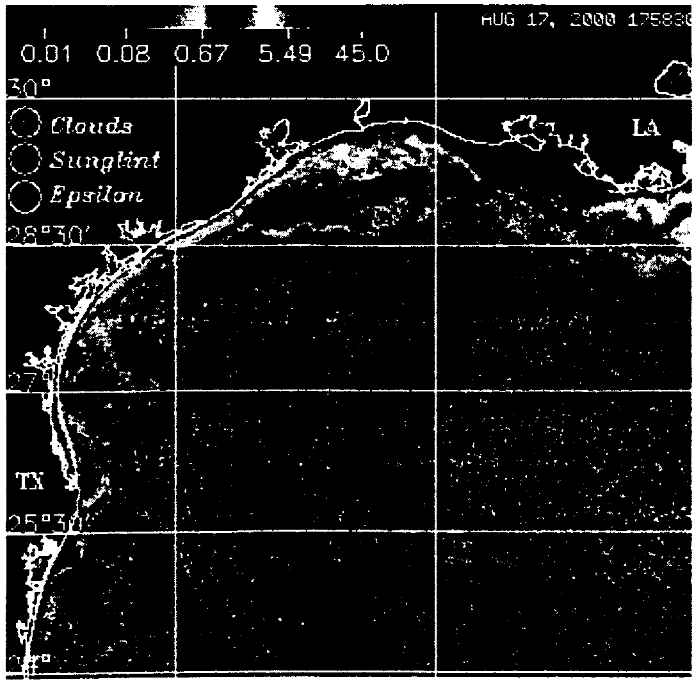


Figure 9. Area of surface offshore water intrusion over SW Texas continental shelf during summer 1998 and 2000.

(a)



(b)

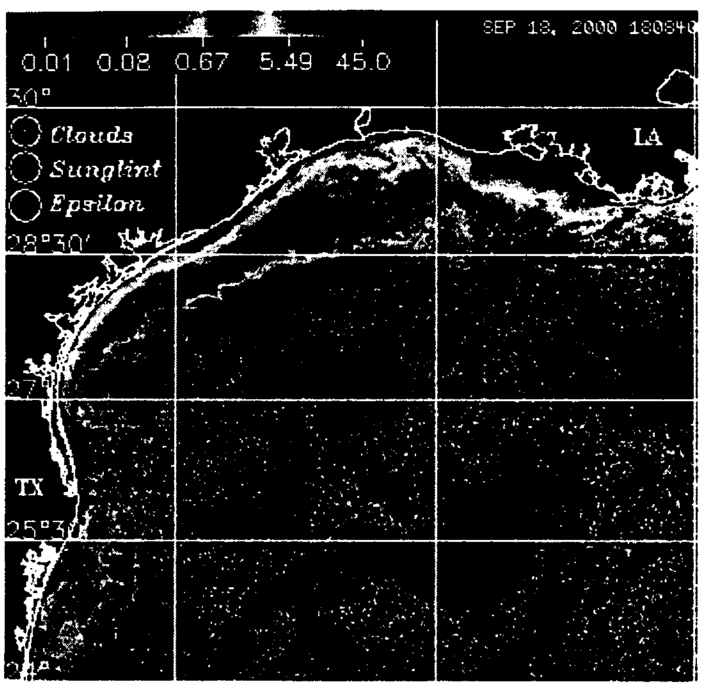


Figure 10. SeaWIFS imageries of NW Gulf of Mexico on 17 August (a) and 18 September (b), 2000.