OBSERVATION OF IMPACTS IN THE GULF OF MEXICO THROUGH SATELLITE IMAGERY

Raúl Aguirre Gómez

INTRODUCTION

The movement of water and sediment on continental shelves, including bays, estuaries and coastal lagoons, has been studied by conventional oceanographic techniques of direct or indirect measurement. Direct observations include the collection of sediment cores or the immersion of automatic measuring instruments (*e.g*. CTD). Indirect observation includes the use of specialized geophysical equipment or the analysis of conservative properties of the water, such as temperature and salinity, through which the origin and movement of water masses can be inferred. These monitoring techniques have been used alone or as part of broader studies. In the last two or three decades, data obtained remotely from air and space platforms have provided an additional source of information for coastal and marine oceanographic research. Satellite images have been used in numerous studies, mainly employing visible, thermal and microwave intervals of the electromagnetic spectrum (EMS). The importance of studying the coastal zone with these techniques lies in the fact that impacts on the coastal zone can be assessed in a synoptic manner.

The objective of this contribution is to do a qualitative assessment of the impact of different anthropogenic activities on natural processes on the coastal zone of the Gulf of Mexico.

GENERAL CHARACTERISTICS OF THE GULF OF MEXICO

The Gulf of Mexico is a semi-closed system with oceanic water entering from the Caribbean through the Yucatán Channel and exiting through the Florida Strait, with a maximum depth of 4,000 m in the central region. One of its most remarkable morphological features is the width of the continental shelf near the Florida and Yucatán peninsulas, which decreases slightly in the north near the coasts of Texas, Louisiana, Mississippi and Alabama and is very narrow on the western slope near the coasts of Tamaulipas and Veracruz.

The Gulf of Mexico is an oligotrophic system with the biggest primary production associated to the presence of northerlies which are present from November to May (Soto and Escobar 1995). The convective mix of the water column appears in October, during the northerlies season, and ends in March. In the northwestern Gulf of Mexico the annual cycle of river discharge is scarce from February to May, and increases during the rainy season between July and September. Discharge from the Rio Grande (Río Bravo), Río Soto la Marina, and Río Pánuco produces an upper layer that can reach up to 100 km from the river mouth, with salinity of 30 psu and a temperature of 21 to 23 °C (Escobar and Soto 1997).

This region of the gulf is formed by a shelf less than 50 km wide that ends at 100 or 200 m depth. The shelf is steep and is distinguished by reliefs that run parallel to the coastline between 24° and 19° N, known as “Cordillera Mexicana” (Mexican Mountain Range). This range acts as a barrier to continental sediment creating a continental slope unique in its nature and origin. The continental shelf near the Yucatán Peninsula is known as the Campeche Bank, and as Campeche Bay in the southwestern region. In the western region of the Campeche Bank there is an area with great depth changes, which is known as the Campeche Escarpment. In the southwestern Gulf of Mexico there is a submarine canyon, known as the Campeche Canyon, which marks the end of the carbonated zone of the Campeche Bank and the beginning of the continental zone.

The region covers several physiographic zones, which include Campeche Bank and Campeche Bay according to the classification of Antoine (1972). Campeche Bank is a very extensive and almost flat carbonated region, delimited on the west by the Tabasco-Campeche basin and on the east by the Yucatán Strait. This region is influenced by upwelling along the Yucatán Peninsula. A strong current derived from the Gulf Current has been observed entering through the strait. It is a shallow zone that encompasses a depth range of 20 to 200 m. Campeche Bay, considered as the marine area of the Tabasco-Campeche basin, is delimited by the 21° N parallel and by the coasts of the states of Veracruz, Tabasco, Campeche and Yucatán to the west, south and east, respectively. The bay opens towards the gulf and borders with the Campeche Bank to the east, and with the Sierra Madre Oriental to the south and southwest. The coastal plain is low, marshy and has poor drainage. Circulation within the bay is influenced by the current from e Campeche Bank, which is produced by the current and upwelling dynamics of the Yucatán (Hernández-Téllez *et al*. 1993). The rainy season, from June to September, brings a supply of freshwater to the bay through the Grijalva-Usumacinta river system. The freshwater input reduces the salinity and modifies the seawater temperature creating a coastal front (Monreal-Gómez *et al*. 1992). The bay is a deeper ocean region ranging from 2,000 to 3,500 m.

The most pronounced physical characteristics are the Loop Current and its associated anticyclonic eddies. Two major rivers discharge their waters in the southern the Gulf of Mexico: the Coatzacoalcos and the Grijalva-Usumacinta river systems. These rivers are the main source of sediments in the coastal zone and represent approximately one third of the fluvial discharge in Mexico (Carranza-Edwards *et al*. 1993). Circulation in this part is cyclonic, and is generated by eddies originating in the east and moving towards the west (Molinari *et al*. 1978). Annual rainfall reaches 4.5 m and there is an average of 160 cloudy days per year.

GENERAL CHARACTERISTICS OF SATELLITE SENSORS

The data used in this chapter were obtained from the Landsat sensors (MSS and TM), SeaWiFS, AVHRR and TOPEX and processed at the Laboratorio de Sistemas de Información Geográfica y Percepción Remota, Instituto de Geografía, Universidad Nacional Autónoma de México (Geographic Information Systems and Remote Sensing Laboratory, Institute of Geography, National Autonomous University of Mexico). These sensors operate in the visible, infrared (IR) and microwave regions of the electromagnetic spectrum. All are transported by heliosynchronous satellites in polar orbit, crossing the Earth equator at approximately the same local time throughout the year. There is a wide range of oceanic and coastal characteristics that are discernible in satellite images. These aspects are described below.

SEA COLOR

In the visible interval of the EMS, satellite images have been used in the study of riverine, lake and estuarine coastal environments and in the deep sea. Diverse sensors have been mainly used in the analyses of sediment and phytoplankton distribution and transport. MSS and TM sensors of the Landsat series and the SeaWiFS sensor of the ORBVIEW-2 satellite are among these instruments.

The main products generated from this type of satellite image are: a) maps of chlorophyll-*a* concentration (pigments) and; b) sediment maps. With these maps it is possible to analyze the distribution and transport of phytoplankton in oceanic zones to infer primary production, and the distribution and transport of sediment to infer possible ecological impacts in the coastal zone.

In the first case, it is possible because the chlorophyll-*a*, which strongly absorbs in the blue region of the EMS with a secondary peak in the red region, is the most abundant pigment of marine algae. Waters with great phytoplankton abundance are characterized by decreasing reflectance (R) in the blue region. The variations in R in the green-yellow interval depend on the combination of the abundance of accessory pigments (chlorophyll-*b* and -*c*, carotenes, biliproteins) and cell scattering properties. The latter is valid in the case of diatoms, which have external silicon shells. The depth at which sea color sensors (*e.g.* SeaWiFS) can obtain information is limited to the first optic depth.

Regarding the second point, near IR is the EMS region used in the detection of sediments. SeaWiFS and AVHRR sensors have spectral bands in this interval. Suspended matter affects the sea color signal in coastal waters. This terrigenous material, which originates from sediments, is resuspended by vertical mixing through the water column, coastal erosion or river discharge. The particles tend to increase the signal reflected by the sea in both regions of the spectrum, by scattering of incident light. The sensors used in the detection of these parameters have spectral, spatial and temporal characteristics. Spectral characteristics refer to the properties of the bands of each sensor. For example, the Multi Spectral Scanner and the Thematic Mapper (MSS and TM) of the Landsat satellites have very wide bands, for which reason they are appropriate for land applications, but present difficulties in the detection of subtle changes in color and reflectance which are typical of the ocean. On the other hand, the SeaWiFS sensor, designed to make sea color observations, has eight narrow spectral bands (20 nm) centered at wavelengths that are particularly useful to detect the weak color signal emerging from the ocean. The spatial resolution of the SeaWiFS sensor is in the order of 1 km^2 observed at nadir. Its temporal resolution is one image per day.

SEA SURFACE TEMPERATURE

Recording the Sea Surface Temperature (SST) by thermal IR sensors is the marine remote sensing technique that has had the greatest impact on oceanography. This is due mainly to three reasons. The first is the high correlation between the digital values of IR images and temperature, with a precision of 0.1°C. The second reason is the continuity in the supply of images by meteorological sensors AVHRR and GOES and, finally, the relative ease to obtain this type of image, which guarantees wide dissemination of information. In order to maintain this situation, IR radiometers must be very precise, well calibrated and acceptably stable. SST images mainly detect the ocean “skin”, i.e., the thickness of the surface layer perceived by satellite sensors in the thermal region (3 to 14 mm) is less than 0.1 mm.

However, in a typical vertical profile of the temperature, a decrease in temperature as a function of depth can be observed. This thermal structure of oceans is characterized by a permanent thermocline at a depth of 1,000 m. Below the thermocline the temperature decreases slowly. Above the thermocline there is a mixing layer with a thickness that can vary from superficial to depths of 50 or 200 meters. This means that if SST measurements are representative for the first meter of water, they will also represent the mixing layer.

SST estimates are derived from satellite images of the NOAA series, from the AVHRR sensor. This instrument has five spectral bands (one visible, one near-IR, one mid-IR and two in the thermal IR). Its spatial resolution is of 1 km^2 at the nadir and its temporal resolution is of 1 image per day (although there are four NOAA satellites in orbit, which guarantees at least four images per day).

The information provided by SST maps is very useful in the detection and identification of characteristics such as ocean circulation, thermal fronts and upwelling; it is also possible to associate SST maps with fisheries (Herron *et al.* 1989) and red tides. Regarding the last aspect, it is known that the massive presence of dinoflagellates or ciliates responsible for red tides coincide with appropriate conditions of temperature, salinity and nutrients. These toxic red tides can affect many forms of marine life. Human beings can also be affected by ciguatera by eating contaminated fish, or by some sort of paralysis by consuming shellfish, mussels or oysters (Kao 1966). Remote sensing of SST has become a very useful tool in the study of red tides dynamics (Peláez 1987; Aguirre-Gómez *et al*. 1999).

SIGNIFICANT SEA HEIGHT

In the microwave region it is possible to make observations of wind and waves, estimate dynamic sea height and significant wave height, among other parameters. The instruments used in this part of EMS can detect both in passive manner, as in the case of the above mentioned sensors, and in active manner if there is an integrated transmitter-receiver. These sensors are mainly radars transported onboard platforms such as the TOPEX/Poseidon, RADARSAT, ERS I and II, among others.

Observation of the sea surface in the microwave region started in 1978, when the SeaSAT satellite was put into orbit. Even though this instrument was operational for a brief lapse of time, the information it provided was of great interest to the scientific community. Its main achievement was the measurement of the distance between the satellite and the sea surface with a precision of 10 cm. This enabled the measurement of the absolute slope of the sea surface, thus enabling the measurement of significant sea height and waves, as well as estimation of wind speed. Satellite altimeters are radars that transmit short signals to the Earth surface. The time taken by the signal to return from the surface indicates the distance between the satellite and the surface, if the speed of propagation of the signal is known. The significant sea height (SSH) in particular is calculated as a function of a geoid relative to a reference ellipsoid, with the same level of precision as the distances to be estimated. Hence, satellite altimetry is an alternative tool to identify eddies, since they are associated with anomalies in the SSH that can be observed at any time of the year.

The TOPEX/Poseidon satellite uses a high precision radar altimeter that can measure SSH in over 90% of the ocean not covered by ice. TOPEX orbits at 1,336 km above the Earth, concluding a cycle of 127 orbits in ten days, with a precision of 2.5 cm. These characteristics allow the satellite to produce topographic maps of the whole world. By knowing ocean topography it is possible to calculate the speed of ocean currents, and the movement of waters can be observed on a planetary level. These changes depend on the latitude and are dominated by the variation of the SST. For example, around the equator it is possible to observe sea level changes during events such as the El Niño Southern Oscillation (ENSO).

Based on these concepts it is possible to identify oceanographic processes in the Gulf of Mexico, and to make both global and regional assessments of various types of impacts. The first of the next sections is dedicated to global analysis, and the second, to the regional aspect.

SATELLITE EVALUATION OF THE GULF OF MEXICO (GLOBAL)

This section describes the main characteristics observed in the Gulf of Mexico by three satellite sensors: The SeaWiFS sensor for sea color, AVHRR for SST and TOPEX/POSEIDON for SSH. These aspects are described in the following paragraphs.

SEA COLOR ANALYSIS

Figure 30.1 shows an image of the Gulf of Mexico taken with the SeaWiFS sensor on April 24, 1998. The image represents the variation in chlorophyll-*a* concentration in the various regions of the Gulf of Mexico. The image corresponds to the winter and aspects of great interest can be observed. The central region of the Gulf of Mexico is mostly oligotrophic as shown by the blue-violet shades that represent concentrations of less than 0.1 mg m^{-3}. Thus it can be inferred that the productive zone of the Gulf is below what can be observed by satellite. Therefore, it can be stated that the mixing layer of the central part of the gulf contains low quantities of nutrients and phytoplankton. In the northern Gulf of Mexico high values can be noticed (red shades) located at the mouth of the Mississippi and Atchafalaya rivers. This signal is the result of the joint response of the concentration of chlorophyll and sediments carried by rivers, which form the dominant part of the signal. Another important characteristic to be observed in the image are the relatively high concentrations opposite the coasts of Tamaulipas and Veracruz. These concentrations are a response to the Mexican anticyclone, as cyclonic structures are formed to its north and south. The Mexican anticyclone is a semi-permanent structure that is directly influenced by the Loop Current (Vázquez 1975). These cyclonic rings promote the ascent of waters with lower temperatures and richer than those in its surrounding (Biggs 1992). The light blue shades represent a relatively high concentration (0.5–0.6 mg m^{-3}) (Fig. 30.1).

Finally, the last general aspect that can be observed in the figure is the influence of the Yucatán dynamic upwelling creating appropriate conditions for relatively high chlorophyll-*a* concentrations in the southern Gulf of Mexico (light blue shade).

SEA SURFACE TEMPERATURE ANALYSIS

The circulation of the Gulf of Mexico is influenced by the warm, saline waters that enter between Cuba and the Yucatán Peninsula, circulate in the Gulf and exit through the Florida Strait, where they join the Florida Current. In the Gulf of Mexico, part of the current forms anticyclonic rings, which influence the adjacent waters, creating cyclonic eddies. The rest of the waters of the current continue on their journey toward the Florida Strait, through the Loop Current. This current is a flow of high salinity water (36.7 psu) and summer surface temperatures between 28 and 29°C, decreasing to 24-26°C in winter. The Loop Current is an intrusion in the Gulf which varies seasonally. During the months of April, May, June and August the intrusion can reach 27° N (Molinari 1978). The current loses strength during the months of July, October and November, reaching only 25° N, creating anticyclone eddies. These anticyclones are warm and saline areas, similar to those of the Loop. The effect of the Mexican anticyclone has been detected off the Tamaulipas coast thanks to the cyclonic rings that promote the ascent of waters with temperatures below those of their surrounding environment. These thermal structures have

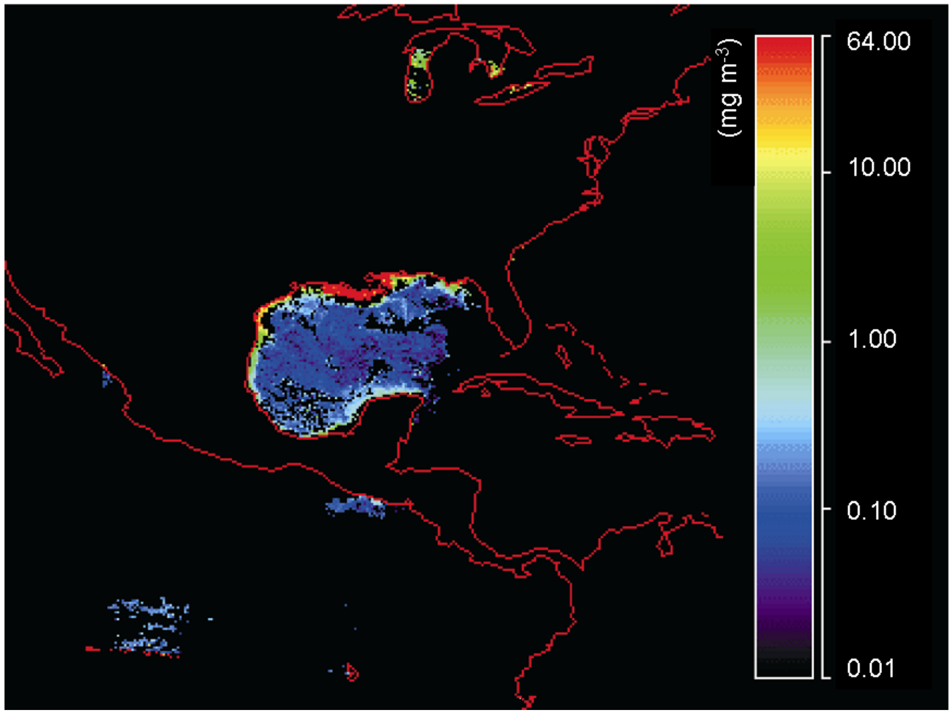

Fig. 30.1. SeaWiFS image taken on April 24, 1998.

been observed and studied with SST satellite images since the mid 1980s (*e. g.* Vukovich and Maul 1985).

Although the Loop Current is a permanent structure in the gulf, satellites can only detect it clearly during the coldest months of the year, because during the warmer months the surface layer in the Gulf of Mexico becomes isothermal due to solar warming, hiding its presence on SST maps. The borders of the Loop Current are clearly visible on satellite images before the surface waters of the gulf become isothermal in May. Figure 30.2 shows a composite of the average SST in February 1998. The Loop Current can be clearly seen in the eastern part of the Gulf of Mexico. The yellow-orange shades indicate temperatures between 24 and 26°C, which contrast with colder waters in the northern zone of the gulf, with temperatures varying between 16 and 20°C (blue shades) and warmer temperatures around 29°C in the Caribbean region (orange shades). These variations in temperature are the result of the interaction of warm Loop Current waters with colder waters, such as those from the delta of the Mississippi River. It is also possible to observe the presence of eddies in the figure, with temperatures lower than those of the Loop Current (green and yellow shades), located to the west of the current and close to the Mexican coast (Fig. 30.2).

SIGNIFICANT SEA HEIGHT ANALYSIS

Important characteristics of the dynamics of the Gulf of Mexico can be seen in Figure 30.3, which can be inferred through altimetry. The figure corresponds to a TOPEX satellite image taken on April 4, 2000. The height of the highest surfaces is related to waters with higher temperature. Thus, the presence of the Loop Current can be observed in dark shades in the

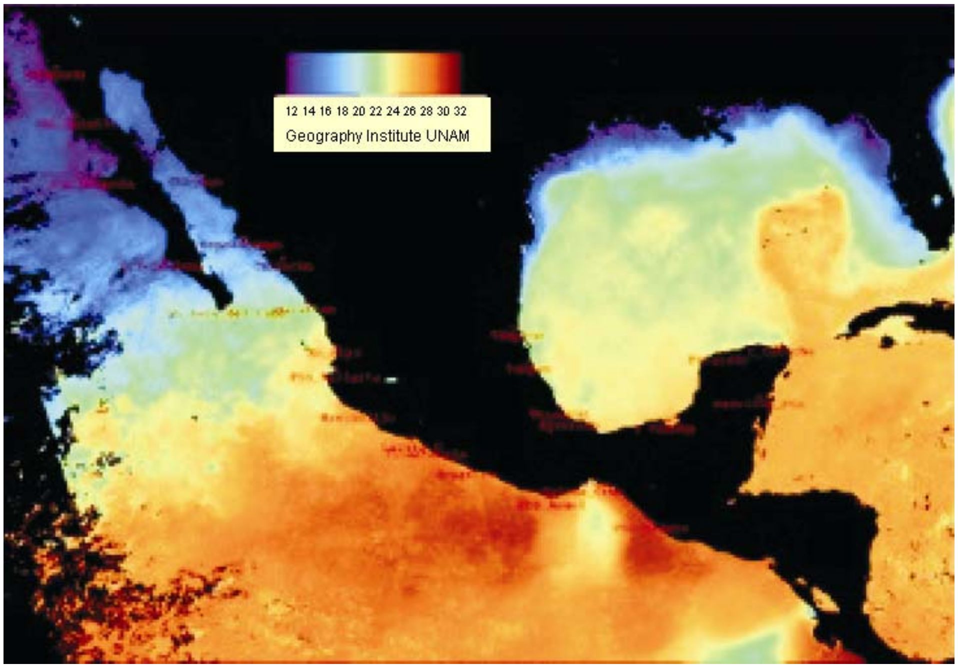

Fig. 30.2. Composite of average sea surface temperature in February 1998.

eastern Gulf of Mexico. Eddies can also be seen, expelled from the main current towards the coasts of Tamaulipas and Veracruz. These structures can remain over variable time scales, can have diameters ranging from tens to thousands of kilometers, and extend to great marine depths. These eddies play an important role in the circulation of the oceans, transporting heat, salts and nutrients. They also have a fundamental role on the climate, fisheries and biogeochemical systems. Observations of differences in heights and temperatures enable estimating the direction of currents and the general circulation of the Gulf of Mexico. In the biological field they can be useful to identify zones where marine organisms live (Fig. 30.3).

REGIONAL SATELLITE EVALUATION OF THE GULF OF MEXICO

COASTAL PROCESSES EVALUATED

In this section an analysis of the coastal region of the Gulf of Mexico through Landsat satellite images is presented. The analysis was carried out from north to south on the states that border the Gulf of Mexico, and includes a case study for each of the states. Regarding the United States of America, an analysis was particularly made for the discharge from the Mississippi and

Atchafalaya Rivers.

In the study of impact on the coastal zone by anthropogenic and natural activities, the discharge of sediments by rivers and by coastal processes of erosion and accumulation are included. The fundamental characteristics of each of these are described below.

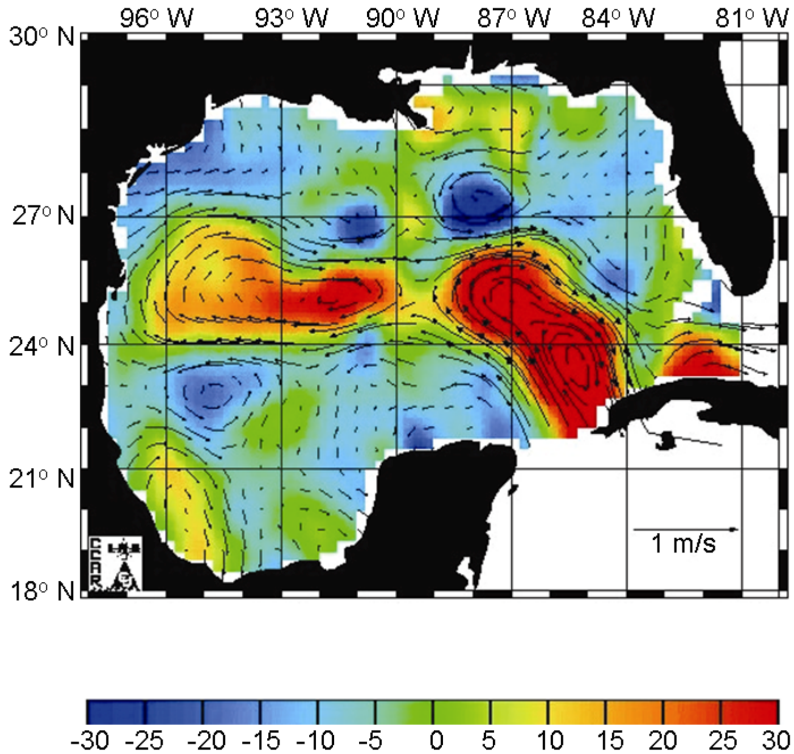

Fig. 30.3. Significant sea height image measured with TOPEX on April 4, 2000.

Discharge of Sediments by Rivers

It is known that sediments carry organic and inorganic material (including contaminants) and are the substrate for different biogeochemical processes that affect the coastal zone in different manners. The plumes of sediments from rivers and estuaries contain relatively high concentrations of organic and inorganic material that is highly reflective in the visible region of the electromagnetic spectrum. This high reflectance is easily observed by sensors located on satellite platforms. The importance of these observations lies in the possibility of knowing the final fate of fluvial nutrients and their possible effect on the carbon balance. In simple terms, this is equivalent to answering the question as to whether nitrates and phosphates produced by agricultural and urban sources, and injected through freshwater discharges on the coastal zone, result in a significant increase in primary production. To answer that question, the understanding of the sedimentation and circulation processes that control the exchange of material through the continental shelf is necessary. The color images of the sea can provide answers to these questions by providing time series images of the formation and dissipation of plumes on continental shelves, and provide an approximation for other processes that affect the rate at which the waters from rivers and oceans mix.

Erosion and Accumulation

It is known that coastal processes change the coastal environment. Regions of contact between sea and land are of intense activity, and the limit between both is what is known as the coastline. This is determined by the position of the sea on the coast over 24 hours. Over periods that stretch from years to centuries or millennia, changes in the position of the coastline can be observed. The factors that influence this variation are wave action, tides and coastal currents. These factors contribute to the destruction of rocks on the coasts, or to the accumulation of sediments they transport. Other factors that influence the changes in coastal topography are the sea level fall or rise due to a larger or smaller contribution of river water. Waves are the main factor of erosion of land edges, which gradually destroy rocky walls by mechanical and chemical action, undermining the continental bases. The Mexican Pacific coasts that run from Bahía Banderas Bay to the Golfo de Tehuantepec are predominantly abrasive. On the coasts of the Gulf of Mexico, on the contrary, it is common to observe a relief comprised of material transported from sea to land. The accumulation processes originate large relief shapes on the coast, such as stretches of beach and barrier islands. These are sand bars parallel to the coast and emerging above sea level in the Gulf of Mexico, stretching for a few thousand km, although not continuously. They completely separate bodies of water such as the Laguna Madre, Laguna Tamiahua, Laguna del Carmen and Laguna de Términos, distributed from the coasts of Tamaulipas to those of Campeche.

REGIONAL COASTAL CHARACTERISTICS

Southeastern Region of the United States of America

The states of Texas, Louisiana, Alabama and Florida are located in the southeastern region of the U.S.A. The coast of the Gulf of Mexico in this region is low and marshy, with abundant mangroves and wetlands. The continental shelf includes the 200 km wide shelf of western Florida, as well as the Louisiana shelf with width varying from less than 20 km in the "bird foot" delta of the Mississippi River to nearly 200 km in the central and western part of the state. Furthermore, the Texas shelf is wide and without any significant changes in its topography. Freshwater discharge in the Gulf of Mexico is around 1,110 km^3 per year and is dominated by the Mississippi and Atchafalaya Rivers, which contribute about 55% of the discharge. The extent of the impact of this discharge is variable and modulated by its rate and the plume dispersion processes, mainly the effect of wind. The influence of the discharge from the Mississippi and Atchafalaya Rivers in the Gulf of Mexico can be seen in Figures 30.1 and 30.2. Red shades Figure 30.1 show a high concentration (above 64 mg m^{-3}) of chlorophyll combined with sediments. Figure 30.2 shows a coldwater current along the southern USA coast, which is associated with the freshwater discharge from the mentioned rivers.

Tamaulipas

The state of Tamaulipas is located on the northern part of the coastal plain of the Gulf of Mexico and in the Sierra Madre Oriental. Its coast is low and sandy, with extensive lagoons closed by the coastline (e.g., Laguna Madre, Laguna Almagre and Laguna San Andrés). Bars have formed at the river mouths. The main rivers are the Rio Grande (Río Bravo), San Fernando, Soto la Marina, and Tamesí. The Rio Grande, in particular, is one of the longest rivers in North America with more than 3,000 km. It forms a natural border between the U.S.A. and Mexico. Both countries use its waters to drink. However, the river has become increasingly polluted as human settlements have expanded along its margins and sewage and pesticides are released into it. Figure 30.4 is a Landsat image of the region where the plume of sediments from the Rio Grande can be seen in the Gulf of Mexico. The magnitude of sediment discharge and its distribution in the coastal zone of both countries can be seen in light blue shades.

Figure 30.5 shows the discharge of the Río Pánuco, which serves as the border between the states of Tamaulipas and Veracruz and flows into the Gulf of Mexico alongside the Río Tamesí. This discharge produces an important ecological impact on the coastal zone since the Río Pánuco is the last stretch in the transport of sewage from Mexico City and other towns along its tributaries, the Tula and Moctezuma rivers (Fig. 30.5).

Veracruz

The state of Veracruz is located between the Sierra Madre Oriental and the coastal plain of the Gulf of Mexico. The coastal plain is surrounded by a low coast with dune formations. Lagoons and marshes are numerous (*e.g.* Laguna Tamiahua, Laguna Alvarado, Laguna Sontecomapan and Laguna del Ostión). All the rivers in Veracruz belong to the Gulf of Mexico watershed. The main rivers in the state are the Pánuco that empties into the gulf alongside the Tamesí, the Tempoal and the Chicayán. There are also the Tuxpan, Cazones, Tecolutla, Nautla, Jamapa, Blanco, Papaloapan-San Juan, Coatzacoalcos and Tonalá rivers. The latter forms the border with the state of Tabasco. The Papaloapan basin, in particular, is a strategic zone for the states of Oaxaca and Veracruz. As in the cases previously illustrated, the discharge from the Papaloapan and Blanco rivers, which pass through the Laguna Alvarado, transports sediments and contaminants. Figure 30.6 shows, in greenish shade in the lower part of the image, the magnitude of the discharge of these rivers during summer, when the flow rate is significant due to rains.

Tabasco

The state of Tabasco is located in the southeastern region of Mexico, and its coastal zone is adjacent to the Gulf of Mexico. The main rivers in Tabasco are those in the lower part of the Grijalva and Usumacinta basins. The origin of these rivers is in the highlands of Guatemala. The Río Grijalva crosses the state of Chiapas northwestward and penetrates the Tabasco plain from the south. The main channel of the Río Usumacinta also heads northwestward, forming the border between Chiapas and Guatemala and then, between Chiapas and Tabasco, it enters the Tabasco plain from the southeast. The Grijalva and Usumacinta rivers merge in the lower reaches of the plain. Their riverbeds are very unstable, and several branches break away originating new rivers that form fluvial islands before flowing into the Gulf of Mexico. In the flood season these rivers flood great extensions of plain forming numerous lagoons and "popales" (shallow lagoons covered with aquatic vegetation) in the lower parts, due to the scarce slope of the terrain and the large volume of the currents, increased by the tributaries that descend from the mountains with an enormous flow rate. The Grijalva-Usumacinta system contributes a little less than 10% of the total discharge of freshwater in the Gulf, although for Mexico it represents 33% (Carranza-Edwards *et al*. 1993). Figure 30.7 is an example of the impressive discharge of the Grijalva-Usumacinta system during the summer of 1976.

Fig. 30.4. Discharge of the Rio Grande (Río Bravo) (Landsat image, November 8, 1972).

On the other hand, low sandy beaches have formed along the Tabasco coast, with predominance of sand barriers and, therefore, there is a series of coastal lagoons: del Carmen, Pajonal, Machona, Tupilco and Mecoacán, among others. The transport of sand along the rivers favors the formation of sedimentary islands through an accumulation process. A clear example of this is presented in Figure 30.8, in the vicinity of the mouth of the Río Grijalva.

Campeche

The state of Campeche is located in the western part of the Yucatán Peninsula. It is a region that lacks mountains, consisting of a plain with hills and small depressions. The northern part is known as La Sierrita. The scarce slope of the terrain toward the coast continues on the continental shelf, with depths of less than 200 meters and width of up to 200 km. This region is known as the Campeche Bay. The south-southwest zones are the lowest and are formed by flood deposits (the rest of the state is limestone). The coast, a little raised in Campeche and Champotón, is low, sandy and with marsh areas in the southern region, where the Laguna de Términos is located, closed in part by the islands of Carmen and Aguada.

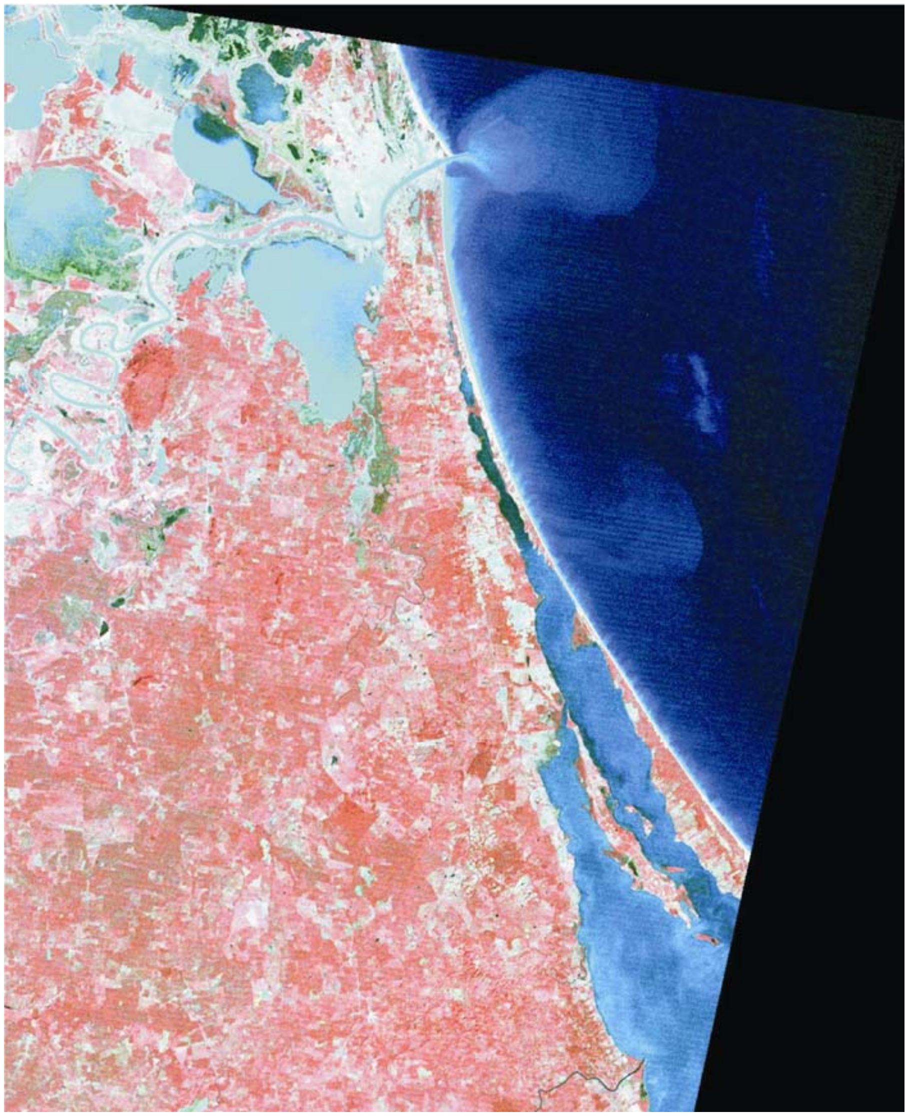

Fig. 30.5. Discharge of the Tamesí-Pánuco and Tuxpan rivers (Landsat image, November 8, 1972).

The main rivers of the state are distributed in several areas. Rivers in the southwest, known as the rivers and lagoons region, include the Río San Pedro y San Pablo, which is a tributary of the Usumacinta and border of Tabasco, as well as those that empty in the Laguna de Términos: Palizada, Chumpán, Candelaria and El Mamantel. Río Champotón is located in the middle of the state. On the west of the Laguna de Términos there are several lagoon systems that open into each other (e.g., Pom, Atasta, del Corte and San Carlos). Erosion and accumulation processes can be clearly observed in the Laguna de Términos. It has two mouths located to the east and west of Isla del Carmen. The eastern mouth, known as Puerto Real, suffers a coastal erosion process caused by the coastal current with a net flow into the lagoon, while the western mouth or del Carmen exhibits a string of beaches formed by accumulation processes through an outwards net flow from the lagoon. Figure 30.9 clearly shows these dynamic patterns.

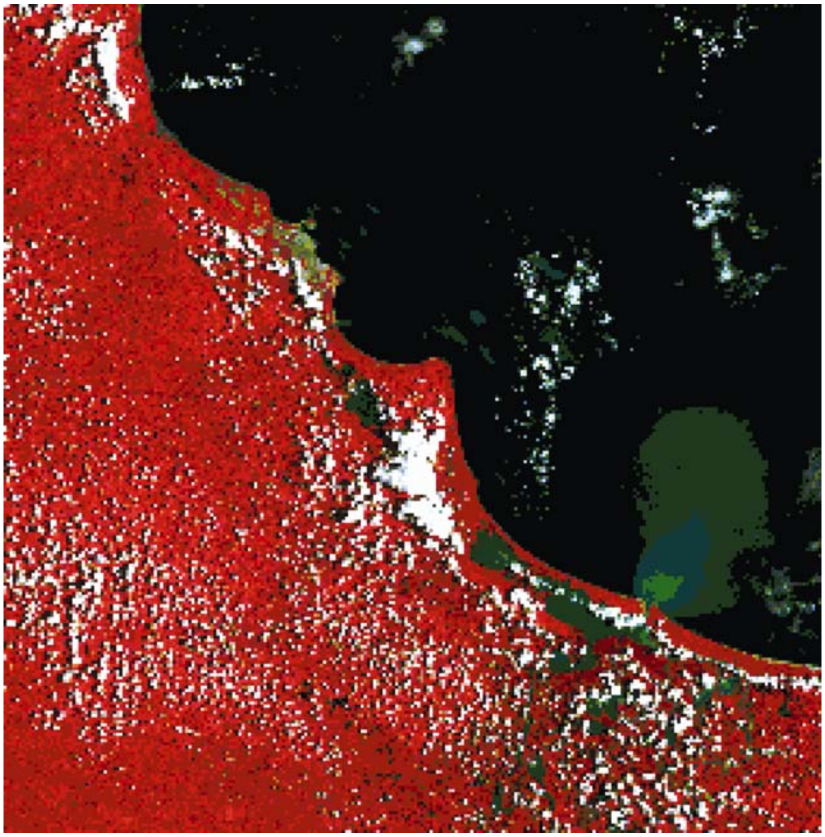

Fig. 30.6. Discharge of the Blanco and Papaloapan rivers (Landsat image, August 26, 1990).

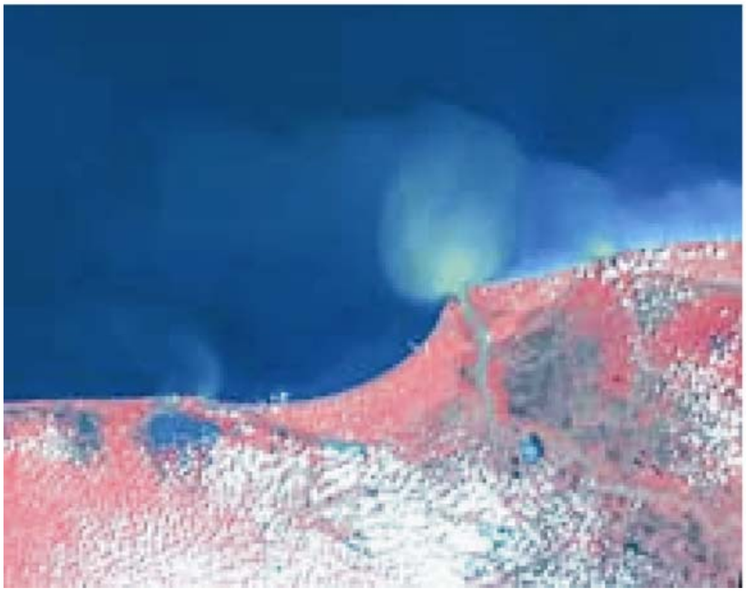

Fig. 30.7. Discharge of the Grijalva-Usumacinta rivers.

Fig. 30.8. Presence of fluvial islands at the mouth of the Grijalva-Usumacinta (Landsat image, September 16, 1976).

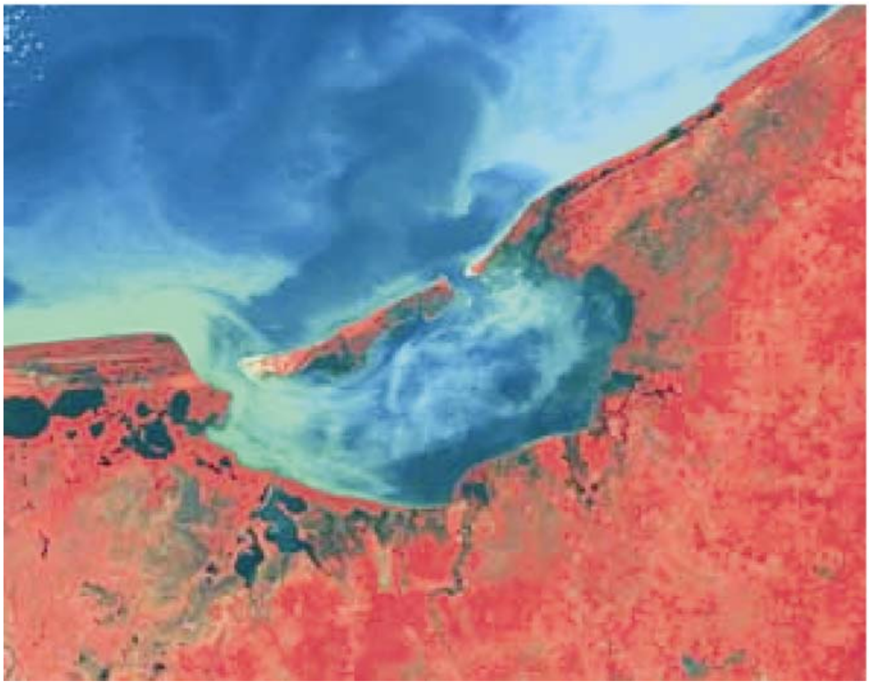

Fig. 30.9. Erosion and accumulation processes in the Laguna de Términos (Landsat image, January 14, 1986).

Yucatán

The state of Yucatán is located in the north central part of the peninsula of the same name. The coast of the state is low, with a wide and sandy coastline on the seaside, deposited by marine currents running east-west along the coast. It exhibits relatively high dunes. Between the sandy strip and the main land there is a lagoon of brackish waters, which stretches along most of the coastline. The part known as Ría Lagartos to the east is remarkable for its length. Most of the rainwater filters directly through the limestone, characteristic of the area, or penetrates through fissures. There are no surface waters; all the water circulates underground, either inside channels open by dissolution of the limestone, or in the aquifer. Groundwater seems to be an important source of freshwater throughout the Yucatán Peninsula. The effect of the Yucatán dynamic upwelling and of the discharge of groundwater from the peninsula can be seen in light blue on Figure 30.10.

FINAL REMARKS

Satellite images are a powerful tool for the analysis of anthropogenic and natural impacts on the coastal zone. They enable the continuous observation of the discharge of rivers and their extent at the mouth, and the assessment of their ecological impact on a region at a given moment in time. The Gulf of Mexico is an excellent region to be analyzed with remote sensing techniques, given its physical, chemical, geological, biological and economic characteristics. I believe that the collaboration of different scientific fields in the study of the Gulf of Mexico environment will result in a greater understanding of the region and, as a consequence, will offer possible solutions to the problems that afflict the system. Oceanography by satellite plays a fundamental role in this process.

Fig. 30.10. Dynamic upwelling at the Yucatán (Landsat image, April 16, 1990).

LITERATURE CITED

Aguirre-Gómez, R., R. Álvarez, and O. Salmerón. 1999. Red tide evolution in the Mazatlán Bay area from remotely sensed sea surface temperatures. *Geofísica Internacional* 38(2):63-71.

Antoine, J. W. 1972. Structure of the Gulf of Mexico. Pp.1-34 in R. Rezak and V. H. Henry (eds.), *Contributions on the Geological and Geophysical Oceanography of the Gulf of Mexico*, Texas A & M University Oceanographic Studies, Vol. 3. Houston, Texas: Gulf Publishing Company.

Biggs, D. C. 1992. Nutrients, plankton, and productivity in a warm-core ring in the western Gulf of Mexico. *Journal of Geophysical Research* 97(C2):2143-2154.

Carranza-Edwards A., L. Rosales-Hoz, and A. Monreal. 1993. Suspended sediments in the southeastern Gulf of Mexico. *Marine Geology* 112:257-269.

Escobar, E., and L. Soto. 1997. Continental shelf benthic biomass in the western Gulf of Mexico. *Continental Shelf Research* 17:585-604.

Hernández-Téllez, J., J. Aldeco, and D. Salas de León. 1993. Cooling and heating due to latent and sensible heat over the Yucatan continental shelf. *Atmósfera* 64:223-233.

Herron, R. C., T. D. Leming, and J. Li. 1989. Satellite-detected fronts and butterfish aggregations in the northeastern Gulf of Mexico. *Continental Shelf Research* 9:569-588.

Kao, C. Y. 1966. Tetrodoxin, saxitoxin, and their significance in the study of excitation phenomena. *Pharmacological Review*18: 997-1062.

Molinari, R. L., J. F. Festa, and D. H. Behringer. 1978. The circulation in the Gulf of Mexico derived from estimated dynamic height fields. *Journal of Physical Oceanography* 8:987-996.

Monreal-Gómez, A., D. Salas de León, A. R. Padilla, and M. A. Alatorre. 1992. Hydrography and estimation of density currents in the southern part of the Bay of Campeche, Mexico. *Ciencias Marinas* 18(4):115-133.

Peláez, J. 1987. Satellite images of a red tide episode off southern California. *Oceanologica Acta* 10:403-410.

Soto, L., and E. Escobar. 1995. Coupling mechanisms related to benthic production in the SW Gulf of Mexico. Pp. 233-242 in A. Eleftheriou, A. D. Ansell and C. J. Smith (eds.), *Biology and Ecology of Shallow Coastal Waters.* Proceedings of the 28th European Marine Biology Symposium, IMBC. Fredensborg, Denmark: Olsen & Olsen Publ.

Vázquez, A. M. 1975. Current and waters of the upper 1200 meters in the southwestern Gulf of Mexico. M.S. thesis, Texas A & M University, College Station, Texas. 108 pp.

Vukovich, F. M., and G. A. Maul. 1985. Cyclonic eddies in the eastern Gulf of Mexico. *Journal of Physical Oceanography* 15:105-117.