Part One

THE PHYSICAL CHEMISTRY OF THE GULF OF MEXICO

THE HYDRODYNAMICS OF THE GULF OF MEXICO

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INTRODUCTION

The Gulf of Mexico is located in a subtropical zone. It is a semi-closed basin that connects with the Caribbean Sea and the Atlantic Ocean through the Yucatán Channel and the Florida Straits, respectively. The bathymetry of the Gulf is very variable (Fig. 1.1): the western part of the Yucatán Channel has a narrow continental shelf of just 2 km whilst to the north of the Yucatán Peninsula the width is 250 km. The Campeche Bank, stretching from the eastern part of the Laguna de Términos to Isla Mujeres, is very extensive and has a gently sloping floor; the continental slope is pronounced and approximately uniform, except in the zone of the Campeche Canyon. The shelf opposite Veracruz and Tamaulipas is very narrow, and gets wider opposite Texas-Louisiana and continuing all the way to Florida. The depth in the center of the Gulf is approximately 3,600 m.

Due to its location the Gulf is influenced by masses of cold, dry air in winter, which come from the continent (Canada, USA and Mexico) and cause the formation of cold fronts when they meet air masses of maritime and tropical origin, which come from the Gulf mainly between October and April (Tapanes and Gonzalez-Coya 1980). The presence of a cold front in the Gulf produces winds that blow from north to south, known locally as “Nortes” (northerlies),

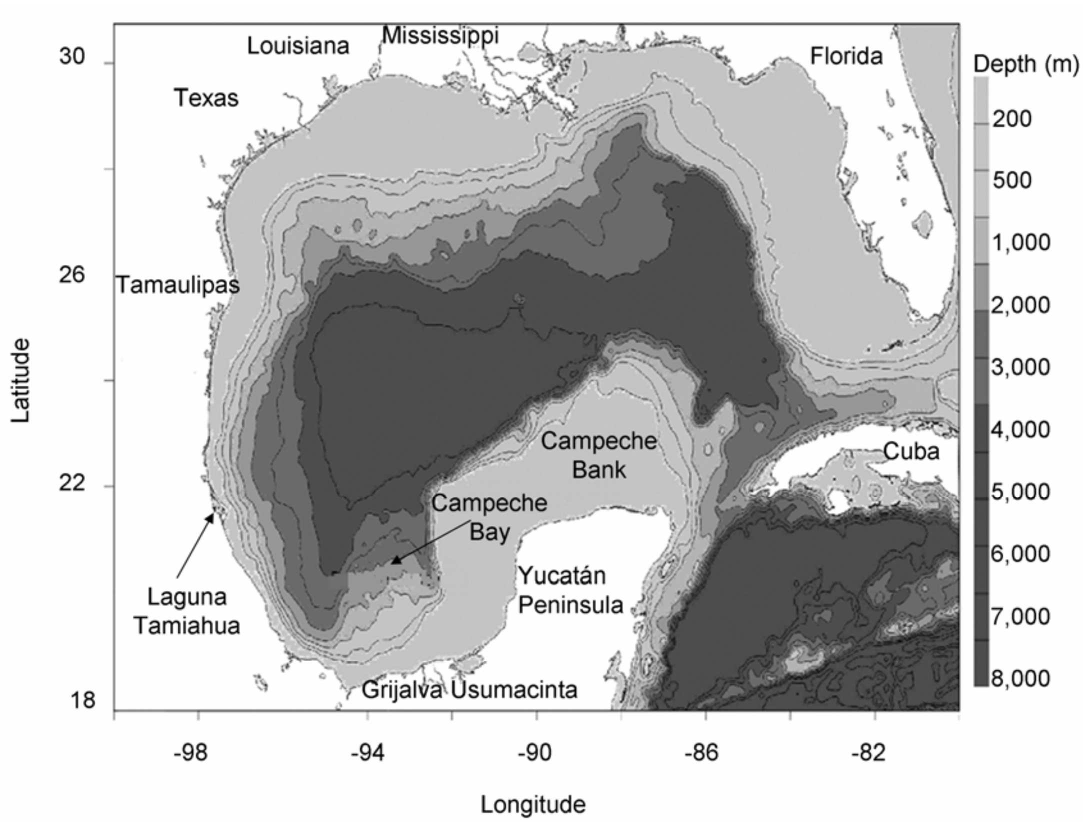

Fig. 1.1. Location and bathymetry (m) of the Gulf of Mexico.

which reach up to 30 m s^{-1}. Cold fronts generate intense winds, and the drop in air temperature when they meet hot and humid air masses forms clouds that can cause winter rains. The extension of the northerlies varies yearly, mainly between “normal” years and years when the El Niño phenomenon is present. When the El Niño phenomenon occurs, the northerlies are less frequent, more intense and reach further south. In the summer the Gulf is influenced by tropical storms of which 60% reach hurricane strength. Most storms generally occur in September.

These meteorological characteristics of the Gulf of Mexico affect not only the coastal zone, due to the discharge of fresh water, but also modify the position of the thermocline, making it deeper and influencing circulation in general. Many diverse techniques have been employed to detect the main circulation characteristics of the Gulf, including the use of hydrographic data *in situ*, numerical models, and altimetry and ocean surface temperature satellite images.

WATER MASSES

Different water masses flow into the Yucatán Channel and enter the Gulf of Mexico at different depths: the Caribbean Subtropical Subsurface Water (CS_tS_sW) is found on the top layer; the Antarctic Intermediate Water (AAIW) is found at greater depth, and at the deepest layer is the North Atlantic Deep Water (NADW). However, a greater number of water masses has been reported in the Gulf (Fig. 1.2). Once the CS_tS_sW is in the Gulf it can be transformed by the convection mixture and thus create two new water masses: the Gulf of Mexico Subtropical Surface Water (GMS_tSW) and the Common Gulf Water (CGMW).

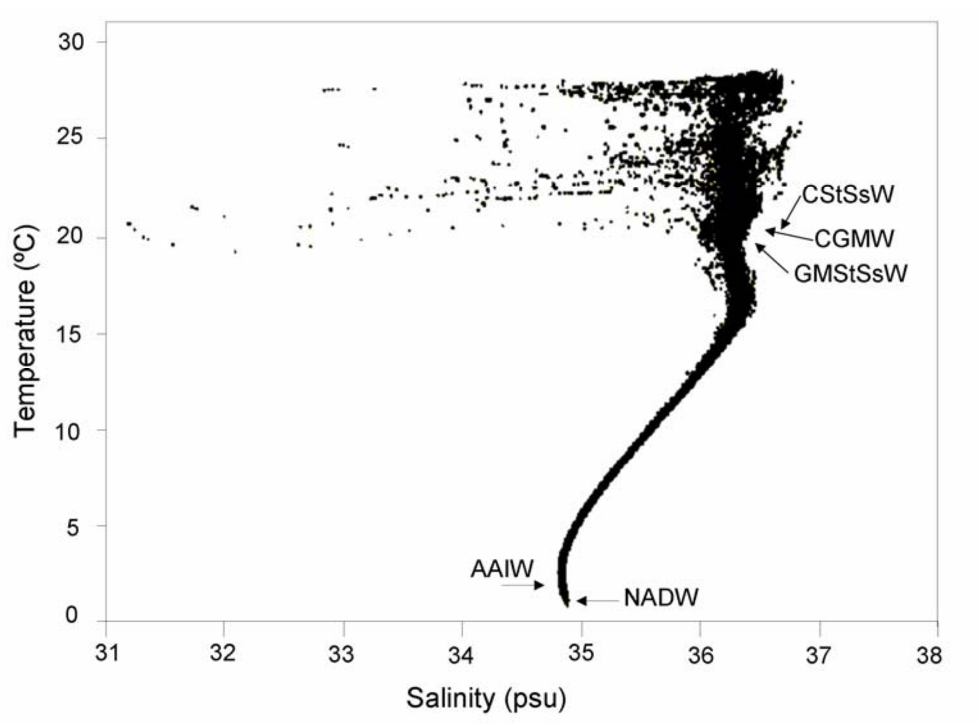

Fig. 1.2. Water masses in the south of the Gulf of Mexico. Caribbean Subtropical Subsurface Water (CS_tS_sW), Gulf of Mexico Subtropical Subsurface Water (GMS_tS_sW), Common Gulf

Water (CGMW), Antarctic Intermediate Water (AAIW), North Atlantic Deep Water (NADW).

The CS_tS_sW is warm and salty with temperatures and salinity values of about 22.5° C and 36.60 psu, respectively. On arrival to the Gulf of Mexico by way of the Yucatán Channel, it forms the Loop Current that frequently encloses an anticyclonic gyre that flows clockwise.

The GMS_tSW is formed inside the Gulf during winter when the cold atmospheric fronts produce a convective mix in the layer at 200 m, which leads to a reduction in the salinity and a significant and latent loss of heat. This transforms the nucleus water of the anticyclonic gyres which break away from the Loop Current into lower temperature and salinity water with values around 22.0° C and 36.40 psu.

The CGMW is formed inside the Gulf as well, through two main mechanisms which share the characteristic of starting as CS_tS_sW. Cooling takes place during the winter months, producing a convective mix (Elliot 1982) which forms the CGMW. However, this mixture only affects the upper layer, which is why the most important mechanism for the formation of this water mass is the collision between the anticyclonic gyre with the continental slope and the continental shelf of Tamaulipas (Vidal *et al.* 1992, 1994b). This collision of the anticyclonic gyre with the continental slope and shelf creates a zone of horizontal divergence and convergence where the subtropical water is diluted by water with less than 36.30 psu salinity, which is located above the main thermocline. The salinity and temperature of the CGMW is about 36.40 psu and 22.5^{o} C respectively and makes up 4.83% of the water in the Gulf of Mexico.

The AAIW originates in the boundary between the Antarctic polar fronts. After its formation it goes northwards near the western Atlantic continental slope, with slight changes in its characteristics and size during its trajectory. In the eastern part of the Caribbean Sea this water mass is found between 700 and 900 m depth, with salinity of 34.75 psu, and in the central Caribbean it is distributed at depths ranging from 650 to 850 m, with salinity above 34.80 psu. On arrival to the Yucatán Channel it is located between 700 and 950 m depth, with temperature of 6.3^{o} C and salinity about 34.86 psu, and in the center of the Gulf of Mexico it is characterized by salinity values of 34.88, at depths between 700 and 850 m. This water mass is identified by the lowest salinity in the Gulf, with salinity between 34.86 y 34.89 psu and temperatures between 6.1 and 6.3° C.

The anticyclonic gyre that comes from the Loop Current moves the remains of the AAIW towards the coast of Tamaulipas at depths between 700 and 1,100 m. This water leaves in small quantities through the Florida Straits. The volume of AAIW represents 73.71% of the water in the Gulf of Mexico.

The formation of NADW takes place mainly in high latitudes, where the high-density water sinks and fills the bottom of the basins with cold water.

Figure 1.2 shows a Temperature-Salinity diagram of measurements taken in the Campeche Bay in summer 1996, and spring and summer 1997. Data was collected in the 1,000 m layer. Low salinities were registered opposite the Grijalva-Usumacinta system, where the temperature variation among different periods is considerable.

The vertical distribution of these water masses is such that the Subtropical Subsurface water and the CGMW are found in the upper 250 m layer. The remains of the AAIW are found in the intermediate layer and NADW occupies the greater depths of the Gulf.

CIRCULATION

The currents system in the Gulf of Mexico originates in the Caribbean Sea. The largest scale circulation in the Gulf is dominated by the Loop Current, which unites the Yucatán Current and the Florida Current through a great anticyclonic gyre, which leaves the Loop Current and travels towards the east like a Rossby wave and the eastern boundary current. In addition to these almost permanent characteristics there are large zones with cyclonic circulation, such as the continental shelf Texas-Louisiana (Cochrane and Kelly 1986; Hamilton 1992), the west Florida shelf and the Bay of Campeche (Monreal-Gómez and Salas-de-León 1990).

There are hydrographic features of smaller scale but very important for the Gulf, such as the seasonal topographical upwelling on the eastern margin of the Yucatán platform, and the saline front due to the discharge from the Grijalva-Usumacinta system, among others.

Several hypotheses have been developed to explain each of the circulation characteristics of the Gulf. However, the majority of studies agree that the flow that enters through the Yucatán Channel and exits through the Florida Straights is the main mechanism that generates circulation.

The flow that enters through the Yucatán Channel varies throughout the year, with maximum flow in spring and summer (Fig. 1.3). Although average flows of 14 x 10^6 m^3 s^{-1} have been reported in the water layer above 500 m, the total flow in the open boundaries has been estimated at 32 x 10^6 m^3 s^{-1} (Schmitz and Richardson 1968). The first reaction of the circulation to the seasonal variation of the flow that passes through the Yucatán Channel is seen through variations in the intensity, direction and extension of the Yucatán current, in the penetration of the Loop Current and in the formation of anticyclonic and cyclonic gyres.

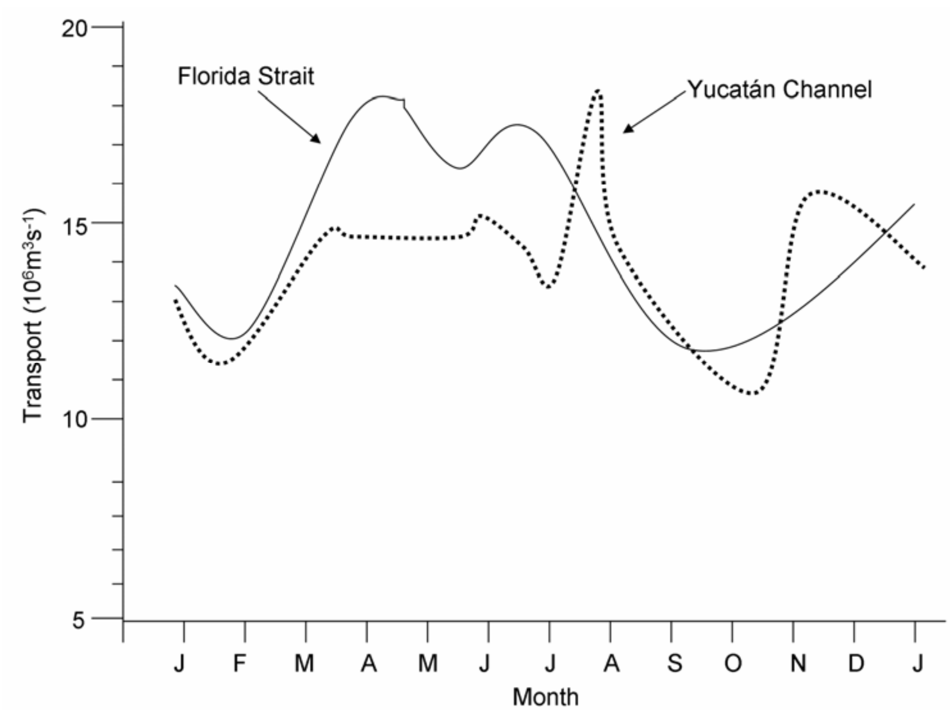

Fig. 1.3. Geostrophic transport through the Yucatán channel and Florida straits in the water layer above 500 m. After Molinari *et al*. (1978).

THE LOOP CURRENT

The CS_tS_sW with elevated salt and heat content enters the Gulf through the Yucatán Channel and moves clockwise (anticyclonic direction), forming a loop-shaped current until the Florida Straits (Fig. 1.4).

The variations in transport across the open boundaries, together with the variation in the incidence angle of the Yucatán current have been considered responsible for the trajectory and extension of the Loop Current, which exhibits maximum intrusion in summer and minimum in winter (Leipper 1970; Molinari and Morrison 1988). This is the general behavior of the Loop Current as its trajectory and intensity vary greatly both seasonally and annually.
The altimetry satellite images that show an anomaly of the sea surface (Sea Surface Height, or SSH) exhibit the extension of the Loop Current on April 15 (Fig. 1.4a) and August 15 (Fig. 1.4b) of 2002. The isoclines with positive SSH values represent anticyclonic circulation, whilst the negative values occur in zones of cyclonic circulation (anticlockwise). The figure that corresponds to the April image shows the formation of an anticyclonic gyre, with the Loop Current confined to the region close to Cuba. Between the Loop Current, the anticyclonic gyre and the Florida shelf there is a cyclonic gyre and an anticyclonic gyre with elliptical shape. On the Yucatán shelf a cyclonic gyre is observed. In August the penetration of the Loop Current reached 27 °N, and the great anticyclonic gyre was found opposite the Tamaulipas shelf. An intense cyclonic movement is noticed to the west of the Loop Current, as can also be observed in the Campeche Bay, and the Florida and Texas-Louisiana shelves. It is interesting to note that in August the majority of the Gulf registers negative SSH due to the lower flow coming through the Yucatán Channel during the previous months (Fig. 1.3); the maximum flow occurs in August creating an intense Loop Current, but this effect is still not seen in the rest of the Gulf. In April there are more areas with anticyclonic circulation, probably due to the increase in the mass flow

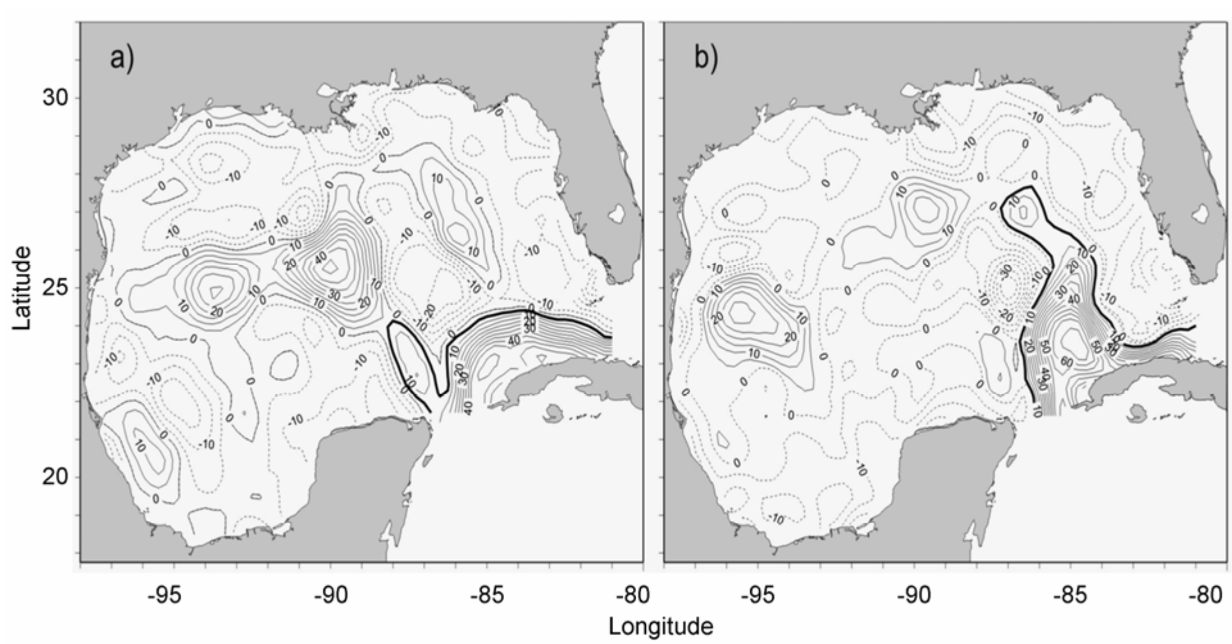

Fig. 1.4. Sea surface height (cm) TOPEX/ERS-2: a) 15 April, 2002; b) 15 August, 2002.

that enters through the Yucatán Channel from February to April, reaching its secondary maximum in April (Fig. 1.3). This gradual increase enables the "filling" of the Gulf and the large number of positive SSH regions (Fig. 1.4a).

The variation in the Loop Current depends on several factors, including the variation in the Coriolis parameter at latitude (effect-b) (Hurlburt and Thompson 1980), barotropic instability, baroclinic stratification and instability, flow variations through the open boundaries, and variations in the incidence angle of the Yucatán Current.

The intrusion of the Loop Current at latitudes greater than 27 °N and the presence of meanders on both sides of the loop favor the squeezing of this current and the breaking away of warm nuclei of high salinity (Elliott 1982).

WESTERN BOUNDARY CURRENT, CYCLONIC AND ANTICYCLONIC GYRES

There is a very intense current towards the north on the western coast of the Gulf of Mexico, which is a response to the variation in the Coriolis parameter with latitude (Monreal-Gomez 1986). This type of current is called "western boundary current". Sturges and Blaha (1976) proposed the name Mexican Current and said that it is similar and almost as important as the Gulf Stream. These authors consider that the winds are favorable to this current and the extension of the Gulf does not limit its existence. However, the wind is not the only mechanism for the formation of the current, with the flow through the Yucatán Channel contributing to it as well (Monreal-Gomez 1986).

The breaking away of the anticyclonic gyre from the Loop Current has been associated with the variation in the flow through the Yucatán Channel, and particularly to the intrusion maximum of the Loop Current. These events happen at intervals ranging from 3 to 25 months, for which reason it is not possible to talk of an average period. Its high variability, which characterizes it as a recurrent but non-periodical process, has to be acknowledged.

Once the anticyclonic gyre breaks away from the Loop Current it moves towards the west (Hurlburt and Thompson 1980) at a translation speed ranging from 2.1 to 4 km d^{-1} (Johnson *et al*. 1992), reaching the western border of the Gulf after several months. During its journey towards the west the anticyclonic gyres undergo changes in size and form, where their radius and eccentricity are reduced due to the dissipation and dispersion of energy. This is why the western anticyclonic gyre is considered a remnant of the one that broke away from the Loop Current. The continental slope promotes the disintegration of the anticyclone and this leads to the formation of smaller or secondary cyclonic and anticyclonic gyres (Lewis *et al*. 1989). The anticyclonic collision with the continental slope originates the Common Gulf Water mass.

The anticyclonic gyres that move westwards contain warm and saline water. They transport energy from the east to the west of the Gulf, have high energy, are found between 22 and 27 °N in the west, and have an average diameter of 300 km.

On both sides of the Loop Current, between the Bank of Campeche and the west Florida shelf, meanders are formed, which generate cyclonic circulation and are later transformed into small cyclonic gyres. When these gyres join they cause the Loop Current to compress and anticyclonic gyres to break off.

Cyclonic gyres with diameters of approximately 150 km are frequent on the Texas-Louisiana, west Florida and Campeche Bay continental shelves. Several mechanisms have been proposed to explain the formation of these gyres, including the cyclonic rotation of the wind force (Vázquez de la Cerda 1993), the meeting of anticyclonic gyres with the continental slope in the western Gulf (Smith 1986; Vidal *et al.* 1994a), the formation of the great anticyclonic gyre, and the geometry of the coast.

The great anticyclonic gyre that journeys towards the west meets the continental slope, loses approximately a third of its mass and transfers its angular momentum, creating two cyclonic gyres, one to the north and the other to the south of the great anticyclone. The tangential speed of the anticyclones and cyclones is 30 cm s^{-1} and 60 cm s^{-1}, respectively (Vidal *et al*. 1994a). Hamilton (1992) studied the gyres to the north of the great anticyclonic gyre near 92 °W, and found that they have diameters between 100 and 150 km and speeds between 30 and 50 cm s^{-1}.

The analysis of dynamic height topography undertaken by Nowlin (1972) shows the cyclonic character of circulation in the Campeche Bay, which has been associated with the cyclonic rotation of the wind force (Vázquez de la Cerda 1993). At the same time, the circulation pattern simulated by a model of reduced gravity shows the formation of the cyclonic gyre and its translation towards the west, as a result of the topography of the bay and the variation in the intensity of the Yucatán Current (Monreal-Gomez and Salas de Leon 1990). This circulation is also reflected in the anomalous distribution of the pycnocline, which surfaces in the center of the gyre (Monreal-Gomez 1986).

During the oceanographic sampling undertaken between August 14th and September 1st 1996 in the Campeche Bay, a medium scale cyclonic gyre became evident by the topographic shape of the 15 °C isotherm (Fig. 1.5a) and the geostrophic circulation (Fig. 1.5b). The isotherm surfaces to the south of 20.5 °N and sinks in the northeastern region of the bay; its surface area is between 140 and 260 m. The geostrophic circulation pattern shows a cyclonic gyre with approximate speeds of 40 cm s^{-1} in the periphery and the southern part of the great anticyclonic gyre in the northwestern part of the bay with approximate speeds of 30 cm s^{-1}.

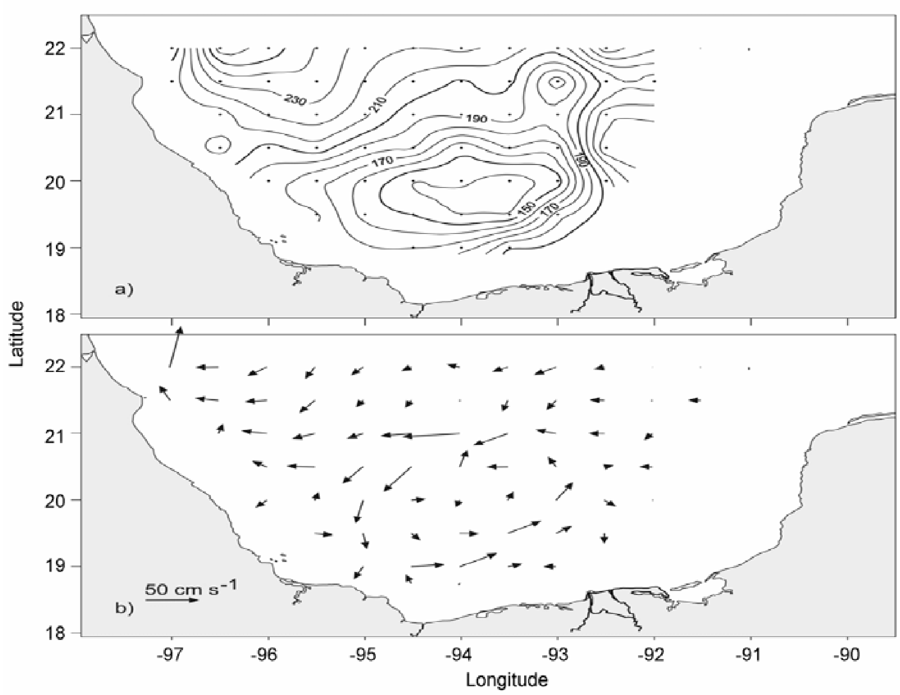

Fig. 1.5. Circulation in the Campeche Bay at the end of summer 1996: a) Topography at 15 °C; b) Geostrophic speed at 20 m depth relative to 1,000 dB.

The general circulation in the Gulf of Mexico is illustrated by the dynamic topography of the sea surface relative to 1,000 dB. In the deepest zone in the eastern Gulf the circulation is dominated by the Loop Current, and on the west Florida continental shelf, by cyclonic circulation. In the center of the Gulf there are anticyclonic gyres that broke off from the Loop Current. In the Texas-Louisiana shelf and the Campeche Bay cyclonic gyres are observed (Fig. 1.6).

Ocean fronts are other characteristics of circulation in the Gulf, which are generally identified by a significant change in the surface temperature (Monreal-Gomez and Salas de Leon 1997). These fronts occur on the boundaries between warm and cold nuclei, i.e., between cyclonic and anticyclonic gyres, as well as between the Loop Current and the cold gyres that are formed on its periphery.

THE YUCATÁN UPWELLING

The seasonal upwelling on the eastern margin of the continental shelf of the Yucatán is topographic. It has been proposed that the friction with the bottom experienced by the Yucatán current when it collides with the continental slope is the mechanism that originates this upwelling (Cochrane 1968; Merino 1997). Another proposed mechanism is the joint action of the Yucatán current and the subsurface countercurrent (García Díaz 1989) located at depths between 150 and 250 m along the continental slope.

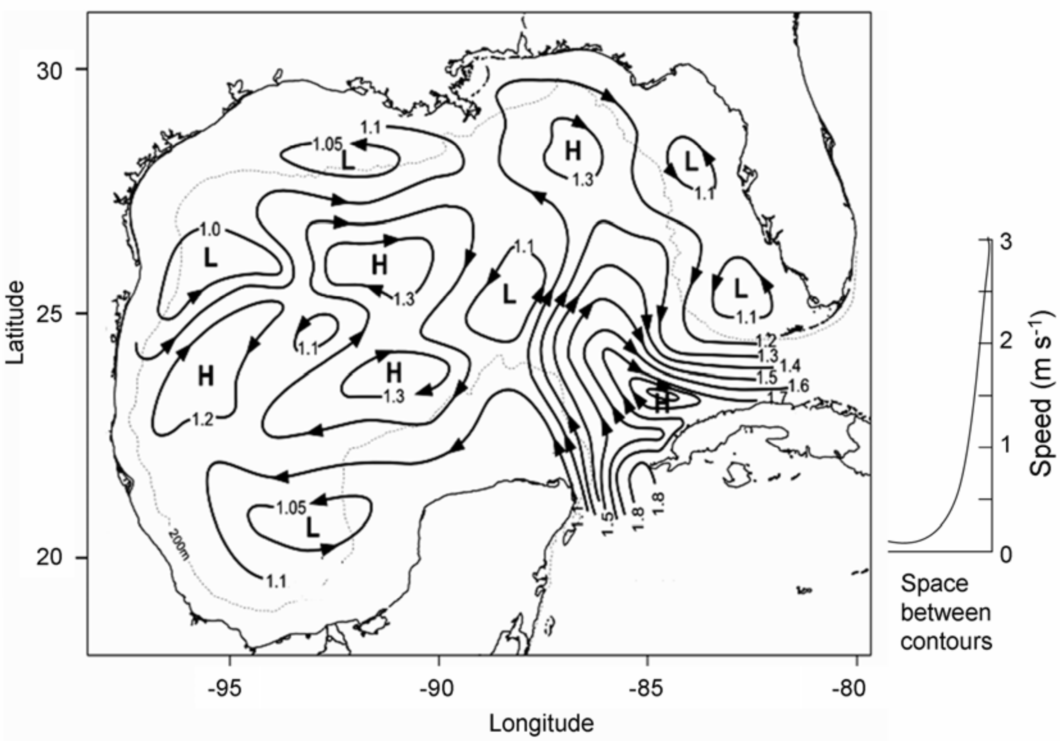

Fig. 1.6. Inferred circulation of the dynamic topography (m din) of the sea surface relative to 1,000 dB. Source: Austin (1955), cited in Nowlin (1972).

The winds of the region were analyzed throughout a year in order to compare this phenomenon with the classic aeolic upwellings. The winds blow from the east, except in winter when they come from the north. As the pattern of winds is similar in spring and autumn, and upwelling is present in the spring but not in the autumn, it has been attributed to the bottom friction suffered by the Yucatán Current, since there is a direct relationship between the intensity of the upwelling and the narrowing of this current (Merino 1992).

The upwelling manifests itself in spring and summer when the Yucatán current is most intense. Its surfacing is seen by the rising of the 22.5 °C isotherm from a depth of between 220 and 250 m (Fig. 1.7a) on the west of the Yucatán Channel, to a depth of between 10 and 70 m over the continental shelf on the north of the Yucatán Peninsula (Merino 1997), exhibiting a cold water dome at Cabo Catoche (Cochrane 1968).

The upwelling water disperses towards the west and gets separated from the continental shelf near Alacrán reef, with speeds of about 10 cm s^{-1} near the coast and 23 cm s^{-1} in the region that is farthest away from it. Based on these speeds it is estimated that the cold water can cross the shelf between 17 and 40 days (Merino 1997). The temperature on the bottom is lower than in the eastern region (14 ºC), rising to 26 ºC opposite the north coast of the peninsula, between 88 and 89 ºW (Fig. 1.7b).

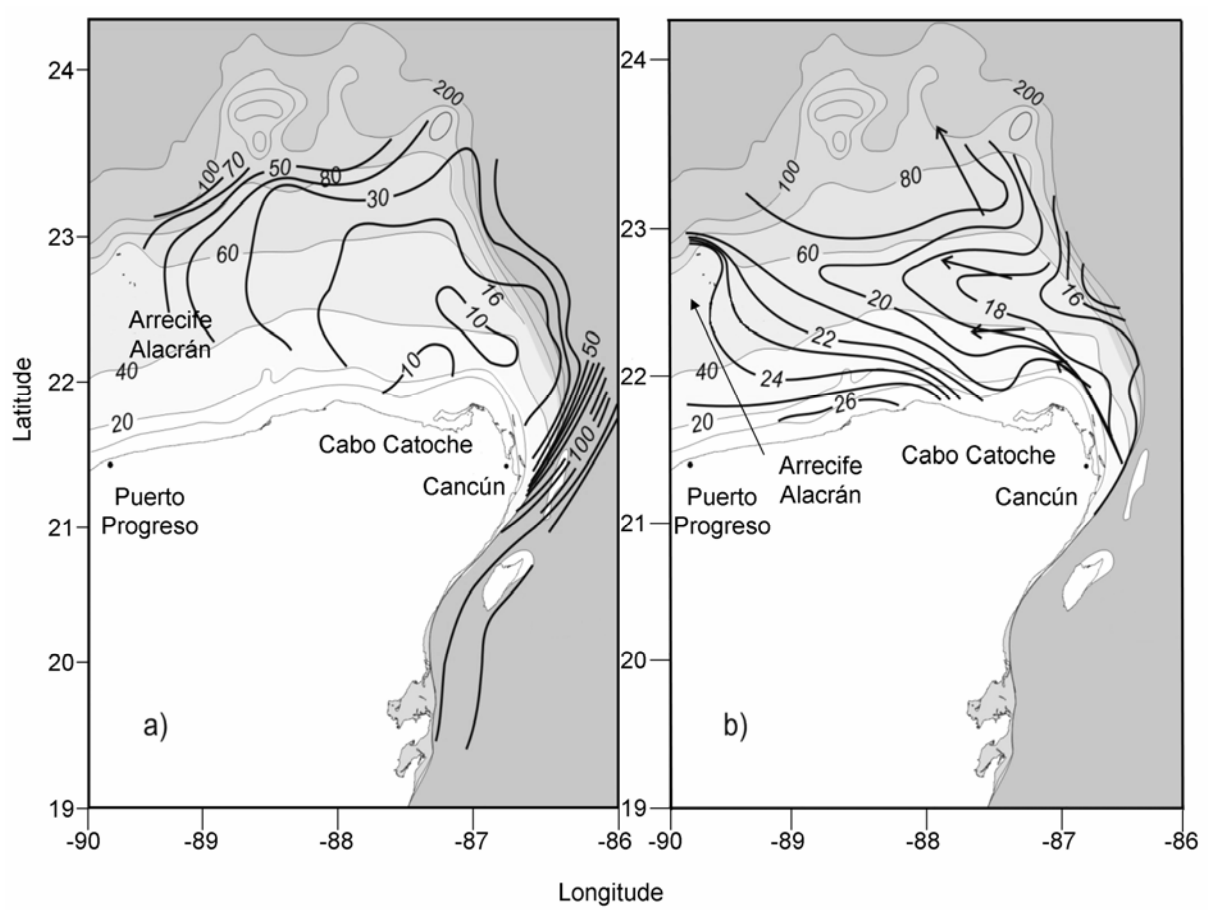

Fig. 1.7. Topographic upwelling in spring: a) Topography (m) of the 22.50 ºC isotherm; b) Bottom temperature and estimated circulation of drift buoys. Modified from Merino (1997).

During the period of upwellings a dome of cold water appears over the shelf, whilst in autumn and winter the majority of the shelf is covered by water with temperatures above 22.5 ^{o}C; on the bottom the isotherms follow the isobars. In winter, before the upwelling develops, the maximum salinity typical of the CS_tS_sW is characterized by its separation from the continental slope and its absence during the upwelling period. This explains the two-layer structure of the continental shelf. This stratification on the Yucatán shelf during spring and summer is not due to the heating of the surface water, but the intrusion of cold upwelling water that covers the shelf.

The geometry of the Yucatán shelf plays an important role in the formation and extension of the upwelling, enabling the upwelling water to remain on the shelf in the euphotic zone for several days, increasing the fertility of the waters.

CAMPECHE CANYON AND CAMPECHE BAY

Campeche Canyon is of tectonic origin, located on the west of the Yucatán shelf, and is a region of complex topography. The zone is influenced by an intrusion current (Vázquez de la Cerda 1979) that flows towards the south. The water near a canyon can move vertically along its axis, favoring the formation of gyres (Ardhuin *et al*. 1999). In the summer of 1999 a hydrographic study showed surface temperatures near 30°C and a 40 m deep layer of mixed water; a warm nucleus at 29°C temperature was detected below this layer, with a 70 km diameter, and another cold nucleus at 25°C occurred at approximately 21°N (Fig. 1.8). The baroclinic circulation shows that these nuclei are associated with the presence of a well-defined anticyclone-cyclone pair from depths of 40 to 300 m. A thermal front is formed between both

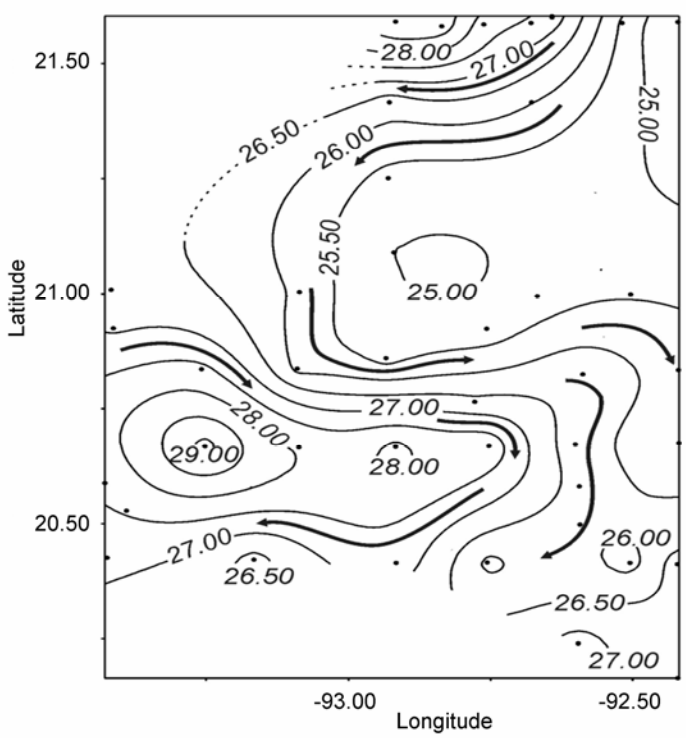

Fig. 1.8. Campeche Canyon: Temperature (°C) at 40 m depth and circulation patterns.

nuclei, which can induce high productivity. It has been proposed that this anticyclonic gyre is of local origin, and that the geostrophic circulation has a current that runs towards the south on the continental slope, which decreases with the distance towards the west, producing a speed gradient and originating the anticyclonic gyre.

In Campeche Bay, the results of a simulation of the circulation produced by a predominantly easterly wind, with a magnitude of 3 m s^{-1} and at the interchange of mass on the north and western boundaries of the bay, show a southward current on the continental shelf. At 92 °W it detours towards the north due to the effect of the coastal current that runs in a northeasterly direction and is part of the medium scale cyclonic gyre that has been observed in the bay; this region registers the minimum elevation of the free surface. In addition, there is a zone of convergence near 21°N, where the cyclonic and the anticyclonic circulations join in the north (Fig. 1.9).

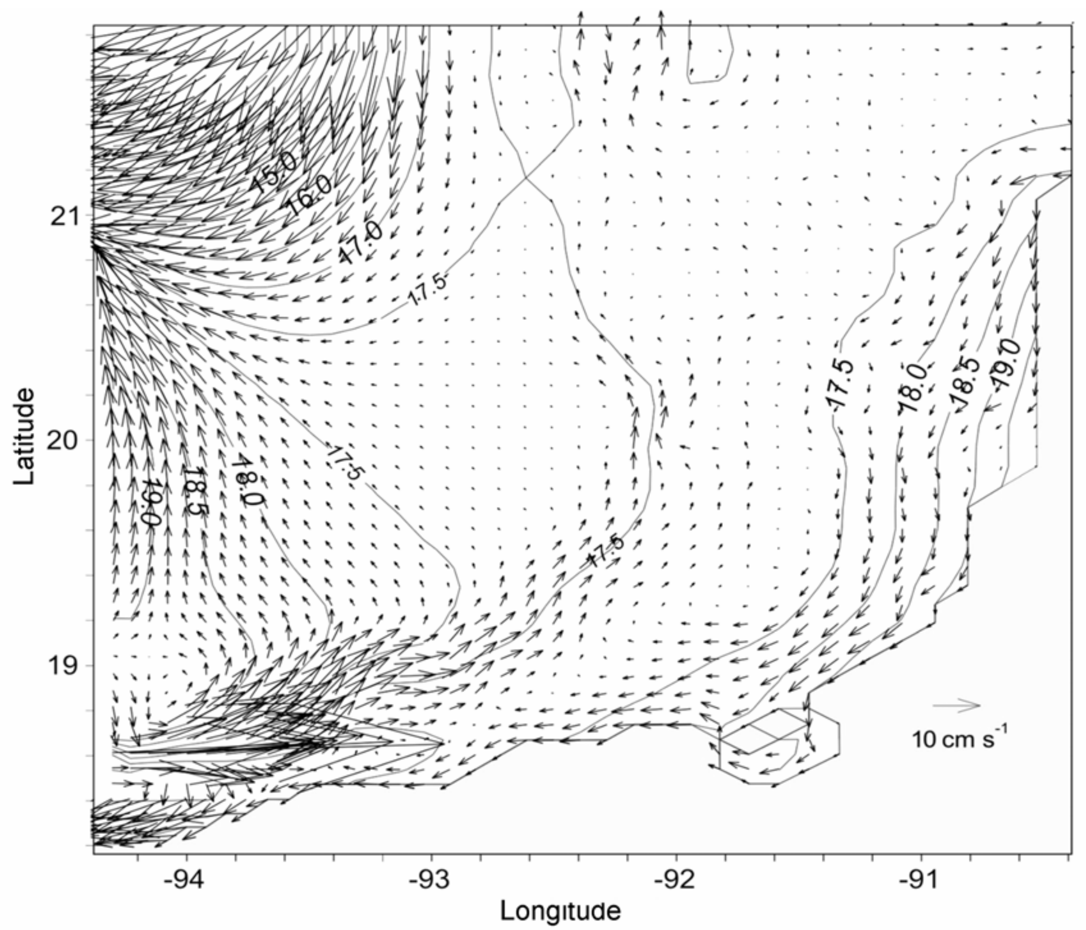

Fig. 1.9. Simulation of the circulation in the Campeche Bay produced by east wind and the geostrophic flow in the northern and western borders of the zone.

GRIJALVA-USUMACINTA SYSTEM

The coastal zone at the mouth of the Grijalva-Usumacinta system is influenced by its riverine discharge, which modifies the water salinity and temperature and, as a consequence, its density. This promotes saline or thermohaline fronts. The most frequent fronts are saline, as a result of the difference between the salinity of the riverine water and the seawater. These fronts are seen by the distribution of the surface temperature, salinity and density.

The Grijalva-Usumacinta system has the second greatest discharge into the Gulf of Mexico, after the Mississippi River. The magnitude of water discharge of the Grijalva-Usumacinta system depends on the meteorological conditions in the area, resulting in a variable volume of discharge throughout the year. Rainfall is heavy during the hurricane season and lower during cold atmospheric fronts. The results of approximately 10 years of research undertaken by the Secretaría de Recursos Hidráulicos (Water Resources Ministry) show that minimum discharges occur in May, and maximum, in October (Czitrom *et al.* 1986). Recently a value of 2,154 $m^3 s^{-1}$ (average between 1948 and 1999) has been reported.

In the coastal zone the density is generally dominated by salinity, whilst in the open sea it is dominated by temperature. In the coastal zone the input of riverine water produces a low salinity region that flows towards the open sea, producing strong horizontal salinity and density gradients when it meets seawater with different characteristics (Fig. 1.10). Generally, a two-layer system is observed, with the upper layer occupied by water from the fluvial system, and the lower layer by seawater. However, the wind and the tidal currents near the coast promote vertical mixing between both layers, thus reducing the salinity difference.

The surface saline front of the Grijalva-Usumacinta system has been monitored at different times: in April 1984 (Czitrom *et al.* 1986), at the end of the autumn of 1987 (Monreal-Gomez *et al*. 1992), and periodically since 1999 as part of the PROMEBIO project (Ocean Processes and Biological Production Mechanisms in the Southern Gulf of Mexico). Initially it was thought that this front was formed when maximum riverine discharges occurred and that a mix would be created and the front disappear when the north wind was intense, suggesting a seasonal character. However, the front has been observed even after intense northerlies (“Nortes”) (Alatorre *et al.* 1989) and with low riverine discharges, for which reason it is considered permanent. Its extension and intensity depend on the magnitude of the discharge, of the coastal currents (Monreal-Gomez *et al.* 1992), and the wind.

Sampling performed at the end of the autumn of 1987 indicated that the isoclines of the surface temperature are perpendicular to the coast and vary between 25.25 and 25.75ºC (Fig. 1.10a). Therefore, an important thermal gradient is not observed. The salinity varies from 33.50 to 37.00 psu (Fig. 1.10b) and exhibits a strong horizontal gradient, which is reflected in the density distribution (Fig. 1.10c). The lowest values occur opposite the mouth of the Grijalva-Usumacinta system, whereas the highest occur to the east, opposite the Laguna de Términos Lagoon, which is a region characterized by high evaporation. The influence of fresh water on the vertical profile is registered until a 15 m depth, extending 50 km into the open sea. The stratification is of the same order of magnitude as that obtained in April 1984 by Czitrom *et al.* (1986). In autumn the main axis of the saline front is towards the west of the mouth, which suggests that there is a coastal current in this direction.

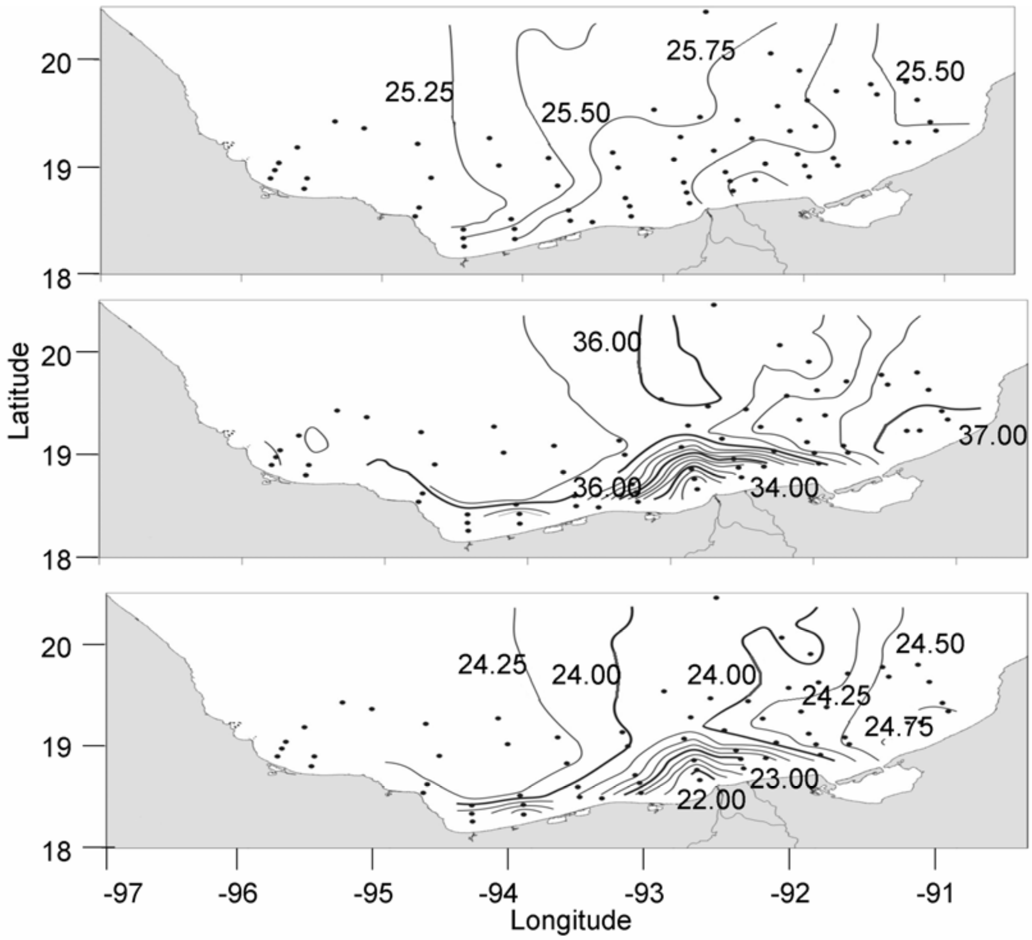

Fig. 1.10. Saline front in the Grijalva-Usumacinta, with surface distribution of: a) Temperature (°C); b) Salinity (psu); c) Density (kg m^{-3}); d) with contour interval of 0.25. From Monreal-Gómez *et al.* (1992).

A hydrographic study undertaken in August 1999 shows the presence of both a saline and a thermal gradient. However, the effect on the density is counteracted between the two, as river water has lower salinity and temperature than seawater.

Coastal fronts such as those generated by riverine discharge in the south of the Gulf of Mexico play an important role from the ecological point of view. Organisms tend to agglomerate near these fronts, and the distribution of waste and contaminants can be affected by these fronts (Klemas 1980). Specifically, during the Ixtoc-I spill in 1978, the front acted as a barrier that prevented the hydrocarbons from reaching the Campeche coast.

ACKNOWLEDGEMENTS

The authors wish to express thanks to A.J. Castro for his support in the elaboration of the graphs.

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