PHYSICAL AND CHEMICAL CHARACTERISTICS OF THE GULF OF MEXICO

Guadalupe de Lanza Espino and Juan Carlos Gómez Rojas

INTRODUCTION

The Gulf of Mexico basin is 1,600 km long from east to west, and from north to south it has a 1,300 km length in its western portion and 900 km in the central and eastern portions. It has a 1.6 million km^2 surface and an approximate water volume of 2.3 million km^3 (Secretaría de Marina 2002). Its tides are characterized by their homogeneity, with predominance of diurnal tides; they generally co-oscillate with the Atlantic Ocean. The Mexican exclusive economic zone has about 0.9 x 10^6 km^2, which represents 55% of the total surface of the Gulf (Vidal *et al.* 1999). It is a diversified interior sea with physical and chemical characteristics resulting from its location, including tropical, subtropical and even temperate latitudes, with a range of climates that are catalogued as “dry (spring), rainy (summer, autumn), and northerly (winter)” periods. There is also the permanent influx of six rivers that drain from Mexico directly into the Gulf: the Pánuco, Coatzacoalcos, Papaloapan, Grijalva-Usumacinta through the Frontera, Champoton and Rio Grande (Río Bravo). On the USA side there is the Mississippi (Fig. 3.1), among others. All these rivers bring a significant amount of suspended sediments and nutrients directly into the Gulf, and create environments such as adjacent lagoons and mangroves, all in a 4,000 km perimeter of coastline from the Yucatán to Florida. No less important is the contribution of different water masses that can increase nutrients content through cyclonic gyres (cold) with the rise of deep water, and the dynamic upwelling on the Yucatán shelf (which shares what is called the Campeche Bank, based on the bathymetric criterion developed by Müller-Karger and Walsh 1991).

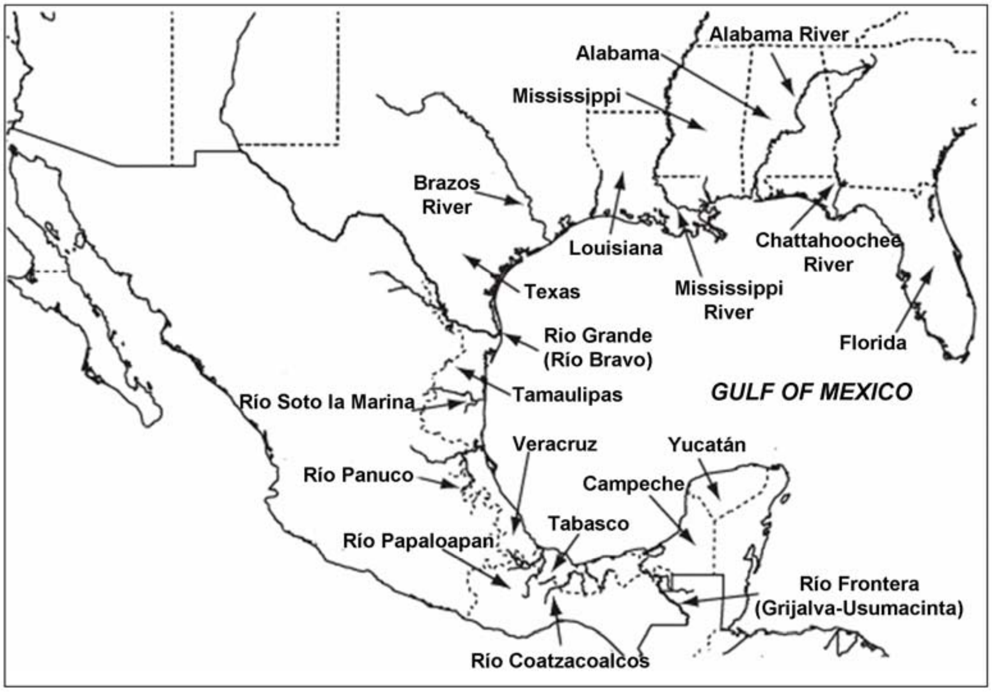


Fig. 3.1. Main rivers that drain directly into the Gulf of Mexico.

In the case of water masses (the depth and extension of these are named differently by different authors), the Intermediate Atlantic Water and the Sub-surface Subtropical Water (or Underlying Subtropical Water between 150-250 m depth) contribute the largest amount of nutrients. Each water mass is identified by its characteristic temperature and salinity and, sometimes, for its oxygen content.

TIDES

Several hypotheses have been proposed to explain how tides are produced inside the Gulf basin. In 1932 Grace (cited by Zettler and Hansen 1972) proposed that the diurnal tide in the Gulf is mainly due to a co-oscillation with the tide of the neighboring Atlantic Ocean, which enters the basin through the Florida Strait and leaves the area through the Yucatán Channel after five or six hours, with a amphidromic point to the south of the Mississippi River delta. This point determines very rapid changes in the tidal phase throughout the delta, as well as on the northern side of the Yucatán Peninsula, promoting an anticlockwise gyre of the cotidal lines. In contraposition to this theory, Sterneck (1920) (cited by Zettler and Hansen 1972) observed a nodal point near the Gulf, but establishing a clockwise tidal front rotation.

Marmer (1954) (cited by Zettler and Hansen 1972) attributes the diurnal tide in the Gulf to the resonance period of the basin, mentioning that this period is close to 24 hours, which is equivalent to the characteristic time of the force that produces diurnal tides. Zettler and Hansen (1972) clarify that the acceptance of Marmer’s theory would require an amphidromic point in the center of the Gulf, which would promote the presence of opposite phases at the extremes of this node.

Another theory postulates the existence of a stationary front in the Florida region. The tidal current in this zone, particularly in the straight, is not small and suggests the presence of a stationary wave node. Amplitude and phase data confirm the presence of an oscillation from a stationary front in the Florida Strait (Fig. 3.2) with a nodal point near Miami. In addition, these harmonic constants on the west of the Caribbean Sea also exhibit small amplitudes (3-9 cm) and rapid phase changes, for which reason it is possible to establish a comparison between the two regions (Zettler and Hansen 1972).

The inertial oscillations inside the Gulf have an approximate period of 28 hours and exhibit an anticyclonic gyre (Brooks and Legeckis 1982; Kirwan *et al.* 1984). Reide and Whitaker (1981) (cited by Kirwan *et al.* 1984) also propose the existence of a 30-hour tidal resonance in the Gulf basin. This information seems to support Marmer’s (1954) ideas in relation to the oscillation period in the Gulf and, in a certain manner, questions the cotidal lines gyre proposed by Grace in 1932.

The tides in most of the Gulf of Mexico (Fig. 3.3) are diurnal ($F=M_2+S_2/K_1+O_1=<3$), with some mixed tides regions such as the northeast and northwest of the Gulf (the Texas-Louisiana, Florida and Mexican Caribbean shelves). The presence of these tides in some regions of the Gulf could be due mainly to the interaction of the tidal front with the dominant topography in each location, as well as to the lunar-solar phases; for example, in the northeastern region, comprised by the Florida continental shelf, the presence of an escarpment and different topographic irregularities, as well as the influence of winds, could promote the formation of mixed tides (De la Lanza Espino 1991).

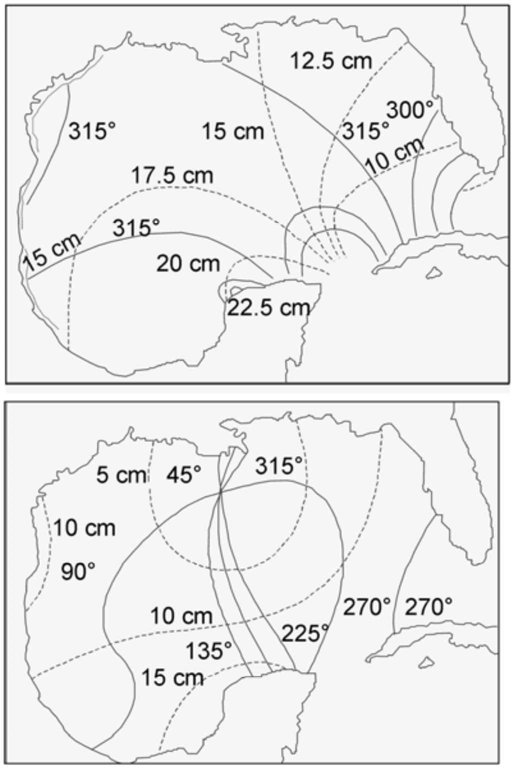
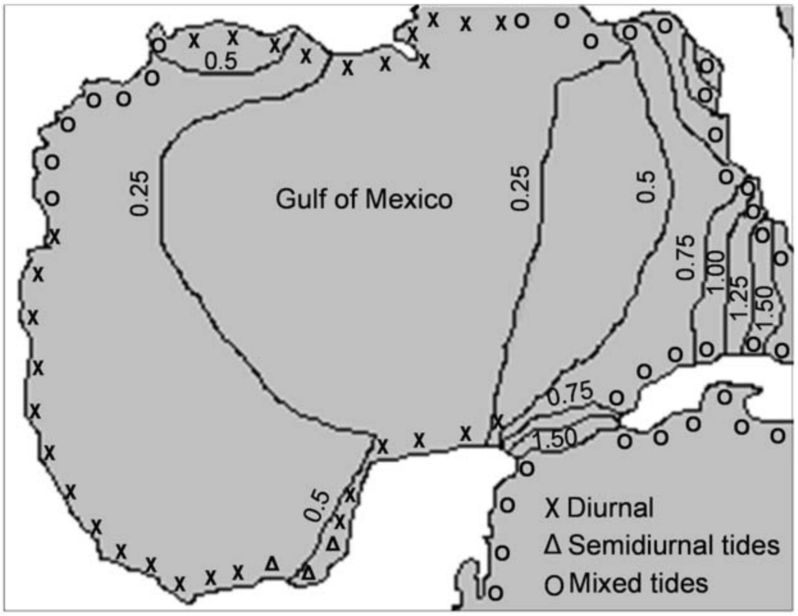


Fig. 3.2. Equal phase lines (-) and equal amplitude lines (—) for K1 (a). Equal phase lines (-) and equal amplitude lines (—) for M 2. Redrawn from Grace (1932), cited by Zettler and Hansen (1972).



Fig, 3.3. Tidal range. F=(M_2+S_2)/(K_1+O_1). Modified from www.ssc.erc.msstate.edu/tides2d/gulf_of_mexico.html (provided by L. Kantha of the University of Colorado).

Sea level measurements taken at different points of the coast of the Gulf of Mexico over a period of 15 years show that the highest sea levels during the four seasons of the year are in Coatzacoalcos, Veracruz (189 to 213 cm), due to the morphological characteristics of the estuary which favors high tidal fronts. While during winter the height is 179.8 cm in Ciudad Madero, Tamaulipas, it is 112.7 cm in Progreso, Yucatán. The Mexican Caribbean coasts exhibit mixed tides (De la Lanza Espino 1991).

TEMPERATURE

The temperature in the Gulf of Mexico is determined by the influx of warm waters from the Loop Current, which enters through the Yucatán Channel and the Caribbean zone, and has a dynamics that affects approximately 50% of the Gulf of Mexico. Furthermore, evaporation is higher than precipitation (Biggs 1992). The Gulf is characterized by a surface temperature of 28 to 29°C in summer, increasing in the surface waters from the northeast to the southeast due to the intrusion of the Loop Current. In winter the temperature drops to 19-20°C as the cold winds from the north resist the warm waters from the southeast, which, in their trajectory towards the northeastern Gulf of Mexico transmit their heat to the lower temperature waters (Nowlin and McLellan 1967). Müller-Karger and Walsh (1991) show that the west and east of the Gulf of Mexico have a similar surface temperature >29°C between July and September, but from December to April the temperature in the western region is approximately 4°C lower than in the eastern region. As the waters in the western region are further away from the influence of the Loop Current, they maintain their minimum and maximum temperatures for long periods relative to the east, where they last less due to the continuous intrusion of the warm Caribbean waters entering the Gulf via the Loop Current.

During winter (January) the surface temperature is 12ºC in the area between the mouth of the Rio Grande and the Laguna Madre, and 10ºC in the northeast on a 110 km area of the continental shelf. These variations are associated with the cooling of coastal waters by northern winds and by the discharge of cold waters from the Rio Grande and Mississippi, Atchafalaya rivers, and to a smaller extent, by the Soto La Marina and Pánuco rivers. Going seawards opposite Matamoros the temperature is approximately 12ºC, and opposite the Río Carrizal it is 15.5ºC. There is an abrupt temperature increase between Tuxpan and Tampico, reaching approximately 22ºC, as a result of baroclinic flux from the transition zone of anticyclonic to cyclonic gyres, which promotes the intrusion of water masses from the Gulf to the continental shelf opposite Tamiahua. The temperature decreases to 16.85ºC opposite the Río Tuxpan, due to the intrusion of water masses from the Gulf, and in Veracruz the temperature of coastal waters is approximately 22ºC (Vidal *et al.* 1994).

The vertical distribution of the temperature in the Gulf of Mexico is a function of the water masses, the local circulation characteristics, the general dynamics of the currents, and the seasonality, which determine the permanence and temporality of the thermoclines. In the northeastern Gulf of Mexico the thermocline begins approximately at 200 m depth, with a thickness of 1,000 m as is shown in Figures 3.4 and 3.5 (Vidal *et al.* 1994). It begins at 50 m depth in the eastern Gulf of Mexico until reaching 4.25ºC at 1,600 m depth (Morrison and Nowlin 1977).

Surface temperatures of 29ºC are registered to a depth of 40 to 60 m on the Campeche shelf (Signoret *et al.* 1998). As the season of the northerlies approaches, the surface temperature

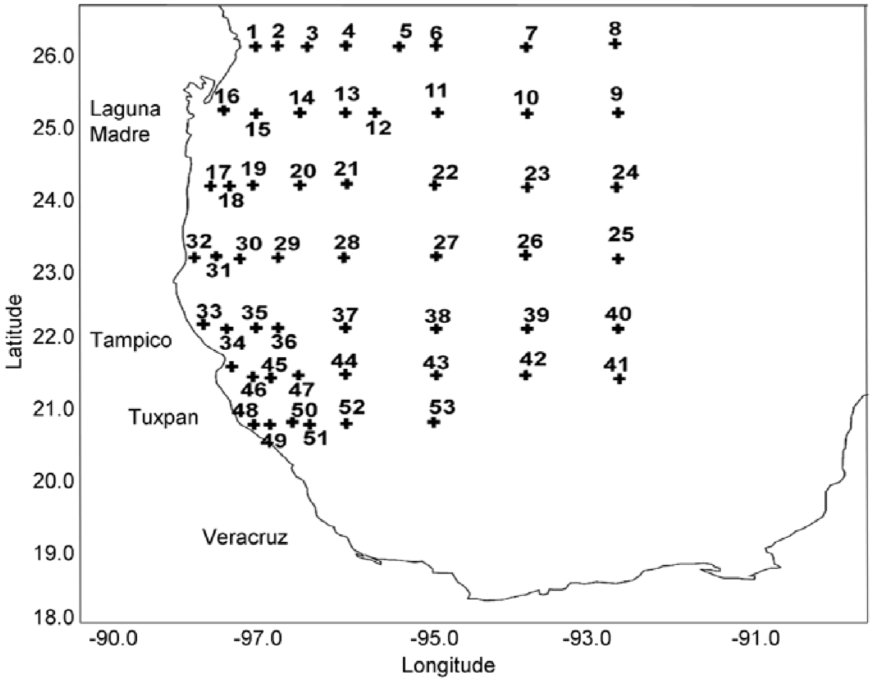


Fig. 3.4. Distribution of the stations studied by Vidal *et al.* (1990).

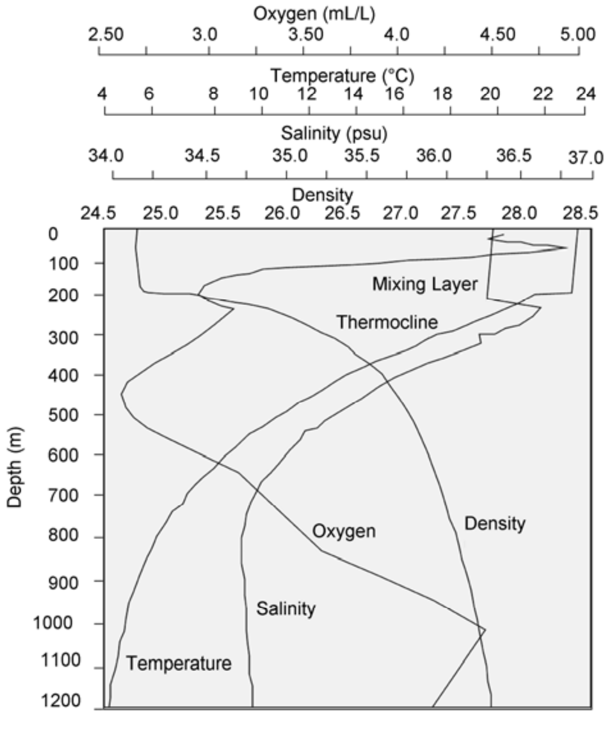


Fig. 3.5. Vertical profile of the temperature, salinity, density and oxygen opposite the Laguna Madre (station 11, 27º N, 95º W) in January 1984. Redrawn fromVidal *et al.* (1994).

of Caribbean waters drops, originating a smaller difference between the surface and sub-surface waters, which leads to a slightly shallower winter thermocline (De la Lanza Espino 1991).

Spatial and temporal vertical temperature variations are observed in the Gulf of Mexico, as a result of the formation of cyclonic (cold) and anticyclonic gyres (warm). The latter are due to the narrowing of the Loop Current, forming isolated rings with similar temperatures to those of the Loop Current. These break away towards the northeast of the Gulf of Mexico, originating a convective type of mix, which transforms the Subtropical Sub-surface Waters in typical Gulf of Mexico waters with a 22.5ºC temperature. There is an anticyclonic gyre opposite the coast of Tamaulipas, due to which warm surface waters sink to depths of 1,200 m. The cyclonic gyres as counterparts of the anticyclonic gyres are formed in their periphery, with the rise of cold waters. The most important cyclonic gyres in the Gulf of Mexico are located opposite the mouth of the Rio Grande and the Laguna Madre beyond the continental shelf (Fig. 3.6), off west Florida, and in the Campeche shelf (Campeche Bank and Campeche Bay) (De la Lanza Espino 1991).

SALINITY

Similarly to the temperature, salinity distribution is strongly related to the Loop Current, which has salinity > 36.8 above a 200 m depth. This is a result of the predominance of evaporation over precipitation in the Caribbean region (Biggs 1992). The salinities in winter are lower in the northern Gulf, at 32.16, due to the season and the influence of rivers (Nowlin and McLellan 1967). In the Campeche shelf the salinity reaches 36.4 to 36.6, which is the highest of

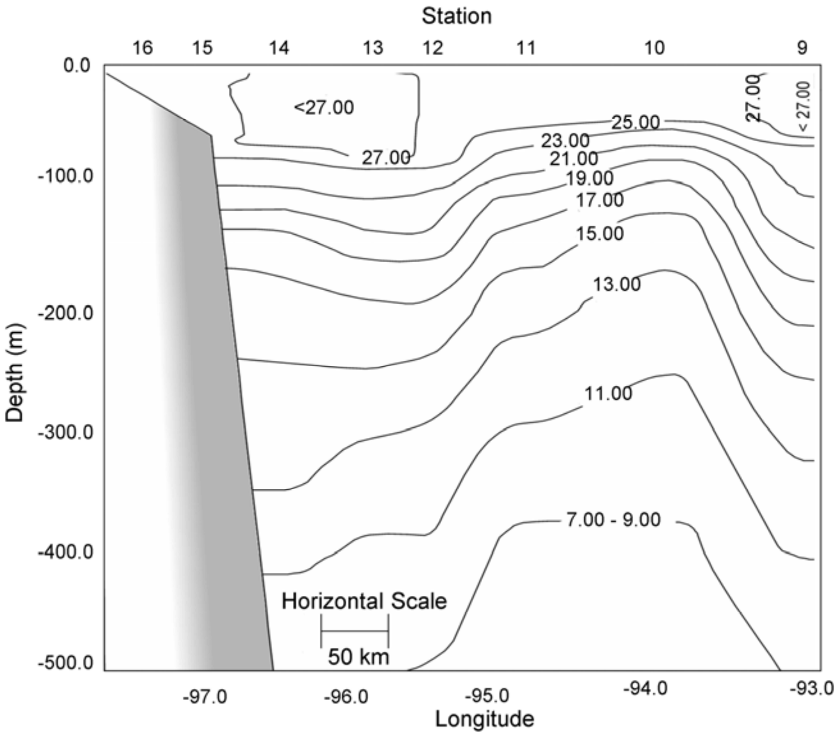


Fig. 3.6. Vertical profile of the temperature (ºC) in the cyclonic gyre opposite the Laguna Madre. Redrawn from Vidal *et al.* (1990).

the Gulf and the Caribbean Current. It is originated by the friction of the surface layers of the Yucatán Current, which touch the shelf of the peninsula and then surface and disperse (Nowlin 1972).

The typical waters of the Gulf of Mexico have a salinity of 36.5, which is due to the mix of the anticyclonic gyres with the Subtropical Sub-surface Water mass, which has a salinity of 36.6 at 70 m depth (Biggs 1992).

According to Vidal *et al.* (1994) the salinity distribution on the western Gulf of Mexico is determined by the direction of the anticyclonic gyres that move towards the north and the cyclonic gyres that move south, as well as by the transition zone that separates them. Minimum coastal salinities of 31.5 occur between Matamoros and Tampico, and the highest occur in high seas, at 36.41 (Fig. 3.5). The low salinity of the coastal waters is related to the discharge from rivers and lagoons, as a product of the dilution of marine with continental waters, characterized by low salinity. Figure 3.7 shows a cyclonic gyre at high seas opposite the Laguna Madre (Vidal *et al.* 1990).

The vertical salinity distribution is related to the water masses that enter the Gulf of Mexico basin, as well as to the effect of the vertical mixing induced by the cyclonic and anticyclonic gyres that dilute the water masses from the upper layers to depths of 700 to 1,000 m. This mixing represents a mechanism that controls the processes of formation and dissolution of water masses inside the Gulf. A layer of minimum salinity (34.8 to 34.9) is observed in the Gulf of Mexico at depths of 500 to 1,000 m, which originates in the Antarctic Intermediate Water

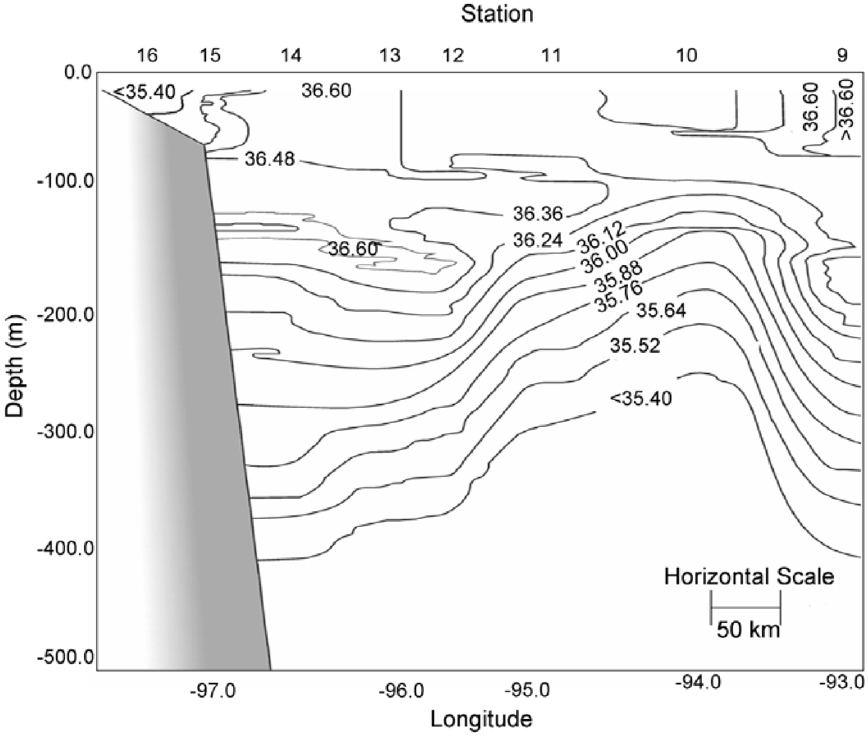


Fig. 3.7. Vertical profile of salinity distribution opposite the Laguna Madre high seas. Redrawn from Vidal *et al.* (1990).

mass (Vidal *et al.* 1990). This layer was described in the Loop Current at a depth of 800 m and salinity <34.9 (Morrison and Nowlin 1977).

Vertical temperature and salinity distribution allow the identification of the water masses that enter the Gulf basin. The anticyclonic gyres that break from the Loop Current and migrate inwards constitute the primary mechanism by which they enter, disperse and dilute the main water masses. It is important to mention that the depths of these masses are approximate, since they are subject to considerable spatial and temporal variations, determined by the baroclinic circulation field of the cyclonic-anticyclonic pairs inside the Gulf of Mexico (Vidal *et al.* 1990).

WATER MASSES

According to Vidal *et al.* (1990) there are seven water masses (Table 3.1); Nowlin (1971), on the other hand, established the existence of six water masses, based on the hydrographic station located in the center of the basin. One of the primary characteristics of the sub-surface oceanic water mass is the presence of Common Gulf Water (CGMW), which is identified by salinity of 36.30 to 36.40, and density between 24.50 and 25.50. This water mass is formed when the anticyclonic gyres coming from the Loop Current collide with the continental slope in the northwestern Gulf of Mexico, as well as in winter when the wind regimens generate a mixing layer of approximately 170 m, which dilutes the Subtropical Sub-surface Water (Vidal *et al.* 1990, 1994).

Table 3.1. Physical and chemical characteristics of the water masses in the Gulf of Mexico (Vidal *et al.* 1990).

Water Masses	Identifying Characteristic	Depth (m)	Density Interval (S_T)	Concentration
Common Gulf of Mexico Water (CGMW)	Max. sub-surface salinity	125-250	24.50-25.50	36.30 to 36.40
Gulf of Mexico Subtropical Subsurface Water ($\text{GMS}_t\text{S}_s\text{W}$)	Max. sub-surface salinity	125-225	25.50-26.30	36.60 to 36.75
18ºC Sargasso Sea Water Mass (18SSW)	Maximum DO	200-280	25.80-26.50	2.80 to 3.50 ml/L O_2
Tropical Atlantic Central Water Mass (TACW)	Minimum DO	300-500 100-680[a]	26.80-27.20	2.40 to 2.80 ml/L O_2
Antarctic Intermediate Water (AAIW) (from 800 m)[b]	Max. dissolved N	300-1500	27.10-27.74	28.70 to 34.90 µM
	Max. dissolved P	400-980	27.25-27.63	1.62 to 1.82 µM
	Minimum salinity	620-900	27.35-27.50	34.89 to 34.91
Caribbean Subtropical Subsurface Water (CStSsW) and upper section of the NADW	Max. dissolved silicates	430-3500	1100-1600[a]	27.26-26.76 21.80 to 26.50 µM
North Atlantic Deep Water (NADW)	Max. rel. salinity	1500-3600 1600-1900[c]	27.76-27.78	34.96 to 34.99

[a] According to Metcalf 1976

[b] According to Pickard 1979

[c] According to Nowlin and McLellan 1967

GULF OF MEXICO SUBTROPICAL SUBSURFACE WATER (GMS_TS_SW)

This water mass comes from the Caribbean Sea and is identified inside the Gulf by its >36.60 salinity, density <25.50 to <26.30, and 22ºC temperature; its presence inside the Gulf of Mexico is due to anticyclonic gyres that break off from the Loop Current in the northeastern Gulf of Mexico (Elliott 1979, 1982). These gyres add seawater from the Caribbean Sea to the Gulf as they break off from the Loop Current.

18ºC SARGASSO SEA WATER MASS (18SSW).

According to Worthington (1959) and Schroeder *et al.* (1959), this water mass is formed during winter in the northern region of the Sargasso Sea, and is characterized by a 36.50 salinity, 17.9ºC temperature, and an inflection in the dissolved oxygen (DO) curve that is manifested by the presence of a second minimum (Kinard *et al.* 1974). The 18ºC Sargasso Sea Water enters the Caribbean Sea through the Windward Passage (between the islands of Cuba and Santo Domingo), at an approximate depth of 300 m, from where it disperses towards the Yucatán and Caiman basins. This water mass was identified in the Florida Current by Worthington (1959). Its presence in this current infers that it enters the Gulf of Mexico from the Caribbean Sea through the Yucatán Strait and is incorporated by the Loop Current. Anticyclonic gyres breaking away from the Loop Current transport the remaining 18ºC Sargasso Sea Water inwards in the Gulf. It is identified by the second minimum dissolved oxygen concentration (≤ 2.80 to ≤ 3.50 ml/L).

TROPICAL ATLANTIC CENTRAL WATER MASS (TACW)

Metcalf (1976) describes it as a water mass with intermediate characteristics between the saltier North Atlantic Central Water and the less salty South Atlantic Central Water. The Tropical Atlantic Central Water is located between 100 and 680 m depth, and is identified by its very low dissolved oxygen concentration of 2.40 to 2.80 ml/L, average salinity of 35.50, approximate temperature of 12ºC, and an average density of 27.20.

ANTARCTIC INTERMEDIATE WATER (AAIW)

This water mass is formed in the Antarctic Convergence, where it is incorporated to the intermediate circulation of the south Atlantic and migrates north in the form of a minimum salinity tongue with a nucleus of 34.30 to <34.50 at a depth of 800 m (Pickard 1979). The remaining AAIW water enters the Caribbean Sea through the Saint Lucia Passages (between the Islands of Martinique and Saint Lucia), with 34.60 to 34.80 salinity (Wüst 1963, 1964). As it enters the Gulf of Mexico and disperses towards the west through anticyclonic gyres that break away from the Loop Current, the salinity of the remaining AAIW increases and the width of its strata decreases until salinities of <34.88 and <34.89 are reached at a depth of 700 to 750 m in the western Gulf (Nowlin 1972; Vidal *et al.* 1986a, 1986b).

CARIBBEAN SUBTROPICAL SUBSURFACE WATER (CS_TS_SW)

The formation of the Caribbean Subtropical Subsurface Water Mass occurs in the Caribbean Sea at potential temperatures between <4.0 and <5.5ºC at depths of 1,100 to 1,600 m

(Metcalf 1976). This water mass is characterized by an approximate 34.93 salinity, silicates concentration between 26.0 and 28.0 μM SiO_4 and density of 27.66.

NORTH ATLANTIC DEEP WATER (NADW)

This water mass enters the Gulf of Mexico via the Caribbean Sea, through the threshold depth (1,600 to 1,900 m) of the Yucatán Strait (Nowlin and McLellan 1967). Wüst (1963) points out that the salinity, temperature and DO range from 34.96 to 34.99, 4.00 to 4.10ºC, and 5.00 to 5.75 ml/L, respectively, at 1,500 to 2,000 m depth in the Yucatán Basin. This constitutes the deep Gulf of Mexico water mass.

Four of these water masses are located in the warm layer (0 to 500 m depth), such as the Subtropical Subsurface Water, the Common Gulf Water, the 18ºC Sargasso Sea Water and the Tropical Atlantic Central Water. The Caribbean Intermediate Water and the North Atlantic Deep Water are located in the cold layer at 500 to 3,650 m depth. According to Vidal *et al*. (1990) six of these water layers enter the Gulf of Mexico through the Yucatán Strait and the anticyclonic gyres that migrate towards the west; the seventh water mass is from the Gulf itself.

OXYGEN

Superficial dissolved oxygen in the waters of the Mexican Caribbean is homogeneous throughout the year, maintaining levels from 4-5 ml/L with a maximum of 6.1 ml/L and 3.2 ml/L at 50 m and 200 m depths, respectively (De la Lanza Espino 1991). Since this water shapes the Loop Current, which represents more than 50% of the water that enters the Gulf of Mexico basin, the oxygen content in the Gulf's superficial mixing layer (0 to 150-200 m depth) is uniform, at 4.5 ml/L as can be observed in the Campeche, Veracruz and Caribbean shelves. Another important characteristic of the Gulf is the presence of the minimum of oxygen layer at an approximate depth of 200 to 600 m, with a 2.0 ml/L concentration on the northwest, and <3.0 ml/L at an approximate 600 m depth in the Loop Current (Morrison and Nowlin 1977). This minimum oxygen layer is also observed in the Gulf water itself (Nowlin 1971; El-Sayed *et al.* 1972) (Fig. 3.8). This layer is a function of climatic factors. Its width depends on local circulation characteristics, since it rises in the cyclonic gyres and drops in the anticyclonic gyres, originating in the Caribbean Sea through the Tropical Atlantic Central Water mass, with similar oxygen content (Vidal *et al.* 1990).

In the northeastern oceanic cyclonic gyre region, which promotes the upwelling of the subsurface layer, the dissolved oxygen concentration is 4.5 ml/L, which is probably associated to photosynthesis (Vidal *et al.* 1990). The oxygen content opposite Matamoros is 6.0 ml/L, and the temperature and salinity reveal a dynamic equilibrium between surface water and the atmosphere (Vidal *et al.* 1990, 1994). Super-saturation has been registered in the Yucatán shelf, with 112% (6.11 ml/L) at 20 m depth (Signoret *et al.* 1998). This is due to high productivity, which results from an oxygen concentration increase with the upwelling. The oxyclines are more superficial opposite the Laguna de Tamiahua and in the area influenced by the Río Coatzacoalcos due to seasonal dynamics factors, as well as to the entrance of river water, with 3.2 ml/L at 60 to 100 m depth (Secretaría de Marina 1972a).

As with the previous parameters, the cyclonic and anticyclonic gyres play an important role in the spatial and temporal oxygen distribution. The surface oxygen concentration can reach 2.6 ml/L in the Campeche shelf at the end of the rainy season, as a result of rising surface waters

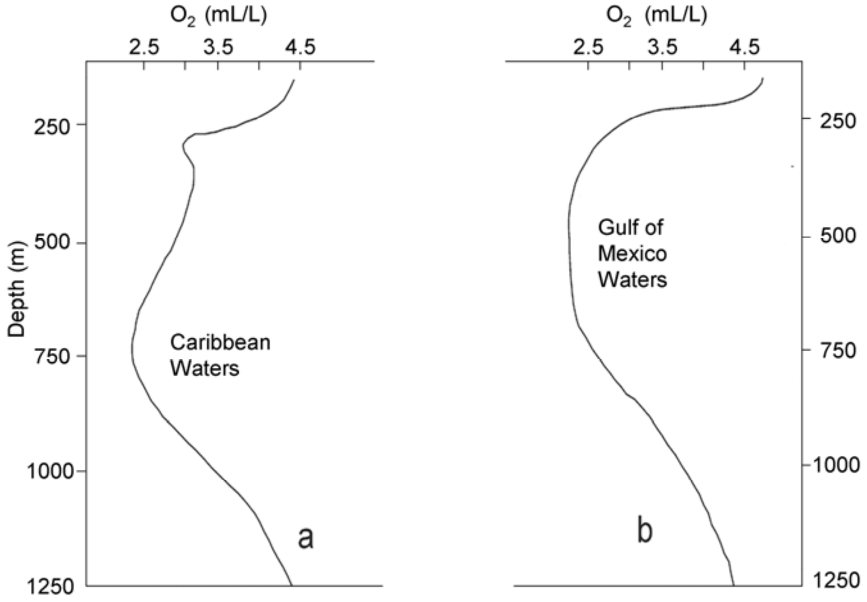


Fig. 3.8. Vertical profile of the concentration of dissolved oxygen in Caribbean waters (a) and Gulf of Mexico waters (b). Redrawn from Nowlin and McLellan (1967).

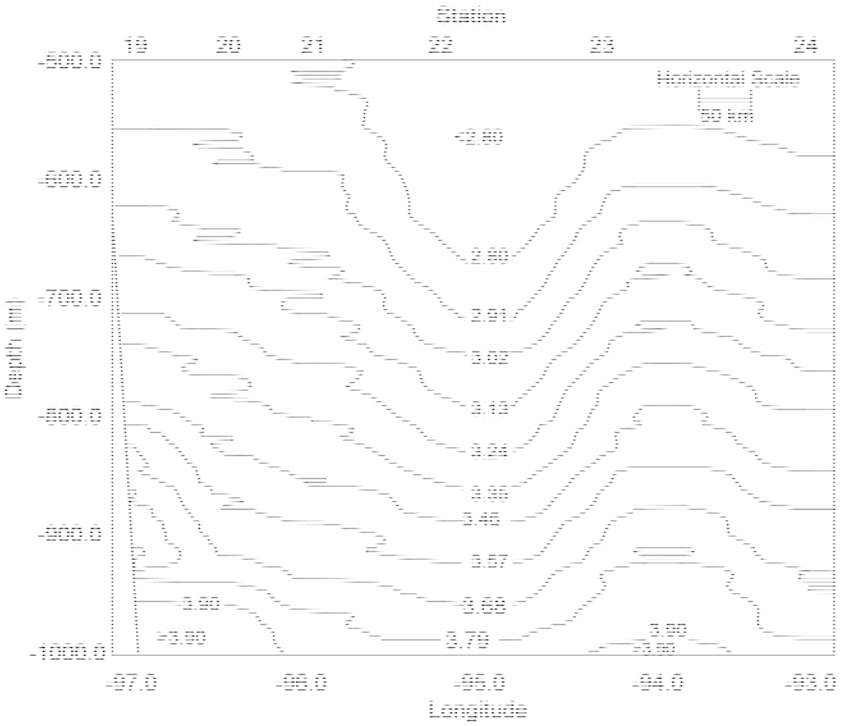


Fig. 3.9. Vertical oxygen concentration profile (ml/L) between the limits of the cyclonic and anticyclonic gyres opposite the Laguna Madre de Tamaulipas. Redrawn from Vidal *et al.* (1990).

due to the cyclonic gyres (Secretaría de Marina 1972b). In the region of the Mexican Anticyclone of Tamaulipas the sinking of surface waters with high oxygen content is observed, forming a vertical profile of 4.45 ml/L to a depth of 1,000 m (Fig. 3.9). Within the limits of the anticyclone and in the center of the cyclone poorly oxygenated water (2.5 ml/L) rises from a 120 m depth. These are the characteristic levels for this region of the Gulf of Mexico (De la Lanza Espino 1991).

NUTRIENTS

NITRATES

The concentration of nitrates in the surface waters of the Caribbean Sea and the Gulf of Mexico goes from undetectable (<0.1 µM) to <0.25 µM in June (summer), and reaches 3.0 to 12.0 µM on the north Yucatán shelf and at 200 m depth (Secretaría de Marina 1980). Cyclonic and anticyclonic gyres define the vertical and horizontal distribution of this nutrient, e.g., in the western Gulf, where the maximum concentrations have been registered in the cyclonic gyres at the latitudes of the Laguna Madre (<28.7 to <34.90 µM at 150 to 300 m depth) (Fig. 3.10). However, 1.75 µM have been detected in the Tamaulipas anticyclonic gyre, which is an anomalous increase due to the sinking of the water mass which promotes a compensatory upwelling in the limit with the cyclonic gyre (Vidal *et al.* 1990).

It is difficult to establish specific concentrations since nutrients are “not conservative” and their content depends on the phytoplankton assimilation and temporality. For this reason nitrate concentration in the mixing layer of the northeastern Gulf of Mexico anticyclonic zone can reach <0.1 µM, and <0.4 µM at 100 m depth (Biggs 1992). During the rainy season 1.20 µM can be registered at the surface opposite the Laguna Madre de Tamaulipas, and at 500 m depth it can reach 30 µM (Moulin 1980). These results are associated with the limits of the anticyclonic-cyclonic gyres, where Biggs (1992) has detected nitrate concentrations >10 µM at 100 m depth. The dynamic of the water masses on the Campeche shelf is determined by the cyclonic circulation, as well as by its intensity, which varies seasonally according to the Yucatán Channel transport. This dynamics largely determines the nitrate concentration distribution. Also, 0.03 µM have been registered in surface waters during the rainy months, and 0.07 µM at 70 m depth. At the beginning of the dry season (spring) these levels rise to 7.26 µM at 10 m depth, due to the surfacing effect generated by the intense circulation composed by the cyclonic rings in this season (Instituto Mexicano del Petróleo 1980). Concentrations of 0.1 to 1.0 µM have been registered in surface waters opposite the Laguna de Términos, and 3 to 13.5 µM at 50 m depth (Licea and Santoyo 1991).

Nutrient rich upwellings occur in the last months of the year and from March to May on the Yucatán shelf, adjacent to the cyclonic gyres zones. In surface waters of the Mexican Caribbean Sea, 1.0 µM and 3.0-12.0 µM levels are maintained at 200 m depth, reaching 25.0 µM near the coast, as a consequence of deep water rising between March and August (Secretaría de Marina 1980). In the area opposite Progreso the upwelling effect is clearly detected through a concentration gradient ranging from 1.32 µM to 4.2 µM from the Gulf towards the coast (Ponce-Velez *et al.* 1991). It is also important to consider the effect of nitrogen and phosphorous enrichment of coastal waters due to inflow of continental waters.

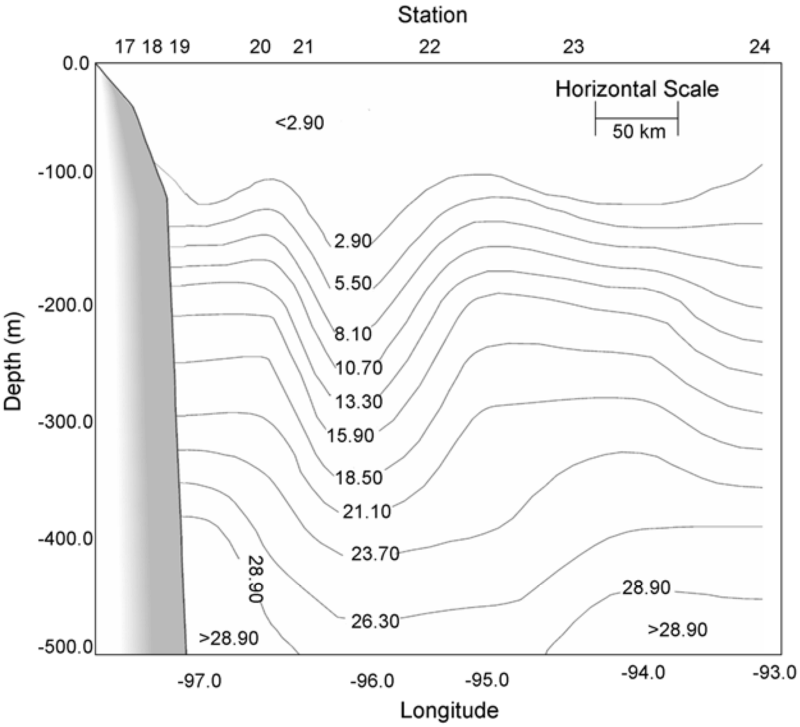


Fig. 3.10. Vertical profile of the nitrate content (µM) in the anticyclonic gyre opposite the Laguna Madre de Tamaulipas. Redrawn from Vidal *et al.* (1990).

The nitrate distribution on the Yucatán shelf in spring exhibits the highest concentrations on the eastern shelf margin, forming a plume towards the west. The 1 µM nutrient isoline corresponds to the limit between nutrient-depleted surface waters at a depth of 100 m, and nutrient-rich (10µM) deep waters (200 m), entering between Arrecife Alacrán and Cabo Catoche (Fig. 3.11) (Merino-Ibarra 1992). The upwelling is strongly related to the Yucatán Current, with a similar annual cycle for speed, reaching maximum intensity in the spring and lowest in autumn (U.S. Department of the Navy 1963). Molinari and Morrison (1988) have demonstrated that the permanence of the current next to the slope is directly related to the penetration of the Loop Current in the Gulf of Mexico, and that the current separates from the slope when the Loop breaks releasing an anticyclonic ring in the Gulf.

The nitrate concentration increases in the upwelling zone during the spring, and its intensity varies among years according to the Yucatán Current speed. The homogeneity on the shelf during winter is due to mixing processes that are capable of totally destroying the stratification that is still present in autumn (Merino-Ibarra 1992). The intensity of the vertical mixing can be higher in winter due to the northerlies, which generate strong waves over the Yucatán shelf and in the Gulf of Mexico.

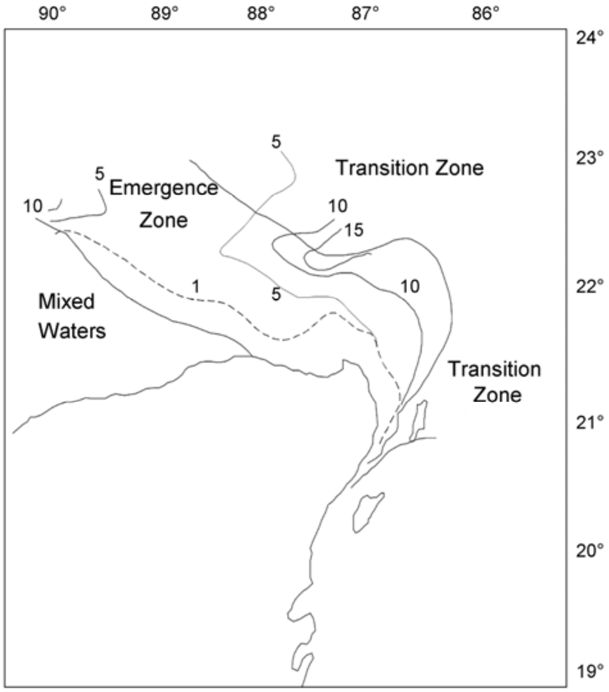


Fig. 3.11. Nitrate distribution (µM) in the Yucatán shelf in spring. Redrawn from Merino-Ibarra (1992).

NITRITES

Nitrites tend to behave in the same way as nitrates, with year-round surface concentrations between 0.05 and 0.1 µM in the Yucatán Channel, and increasing to 0.25 to 0.30 µM towards the coast (Secretaría de Marina 1980). Due to the upwelling effect in July, levels of up to 0.45 µM have been registered in the Yucatán Peninsula (Merino-Ibarra 1983). In the western Gulf surface waters the levels reach 0.2 µM, rising to 0.3 to 0.4 µM at depths of 400 m and decreasing near the cyclonic and anticyclonic gyres (Moulin 1980).

ORTHOPHOSPHATES

The orthophosphates content is low in surface waters, ranging from 0.1 to 0.8 µM year-round with an increase to 1.8 to 2.5 µM at depths of 800 to 900 m. On the Campeche shelf the most frequent concentrations are from 0.11 to 0.13 µM, similar to those in the Loop Current (Morrison and Nowlin 1977). Surface orthophosphates concentrations in the western Gulf are below the detection limit (<0.03 µM) and the largest content is on the coast, at <0.13 µM, due to the fluvial contribution that stimulates primary production in this region. In the northern cyclonic gyre orthophosphate concentration is 0.12 µM due to the upwelling (Vidal *et al.* 1990).

Bogdanov (1969) points out that the Campeche shelf surface waters exhibit levels of 0.11 to 0.13 µM, similar to the Loop Current, tending to increase till 100 m depth, reaching 0.66 µM. The cyclonic circulation favors orthophosphate enrichment at the surface through the rising of

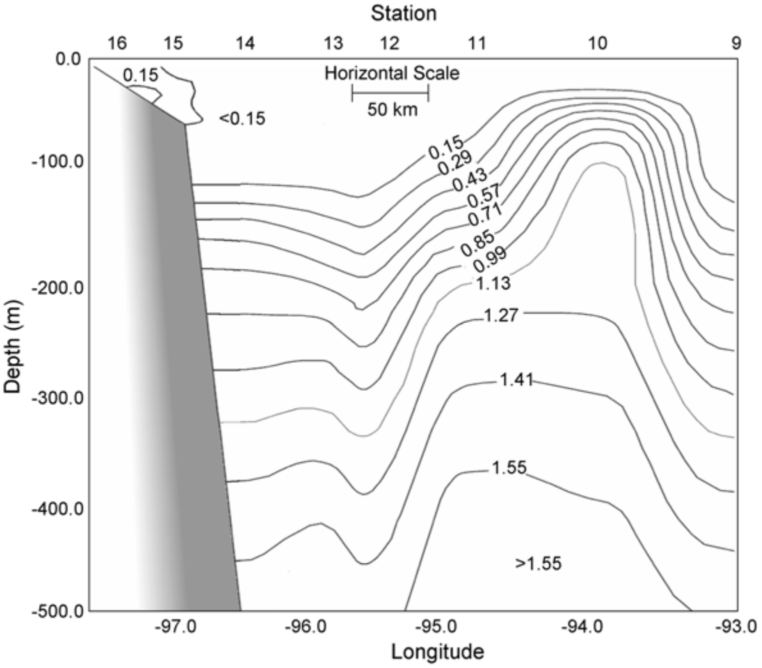


Fig. 3.12. Vertical profile of orthophosphate concentration (µM) in the cyclonic gyre opposite the Laguna Madre. Redrawn from Vidal *et al.* (1990).

deep waters (Fig. 3.12). The surface maximum on the Campeche shelf, between 1.09 and 1.19 µM, occurs in spring. In addition, this area receives the input from the Río Grijalva, opposite which 1.32 µM concentrations have been detected. Such concentrations decrease to 0.11 to 0.2 µM in the first meters. The highest measured levels in the annual cycle have been detected in autumn, with 2.95 µM from the surface to 50 m depth, as a result of the intensification of northerlies and cyclonic gyres (Instituto Mexicano del Petróleo 1980; Segura *et al.* 1982).

In the western Gulf of Mexico opposite the Tamaulipas coast the surface orthophosphates maintain levels of 0.1 to 0.3 µM to 100 m depth, with peripheral emersion and central sinking thereafter; within these limits 2.5 µM are measured at 200 m depth, which is characteristic of water >700 m depth elsewhere in the Gulf (Moulin 1980).

A minimum surface concentration of 0.01 µM is observed in the vertical distribution of orthophosphates, which is the same as for nitrates. The maximum concentration (<1.62 to <1.82 µM) occurs at 500 to 1,000 m depth, which derives from the Antarctic Intermediate Water (Vidal *et al.* 1990).

In general, the field of barometric circulation determines the spatial distribution of dissolved nutrients in the Gulf of Mexico. The vorticity of the gyres and their joint interaction generate a natural pumping system inside the Gulf, given that they transfer vertical upward and downward movements of the water masses that occur in the region (Vidal *et al.* 1990). In addition, it is worth clarifying that their spatial and temporal variation depends largely on the phytoplankton assimilation and their blooms.

SILICATES

This nutrient is one of the least frequently evaluated. However, acceptable information is available in the Gulf of Mexico to establish its behavior. In the waters of the Yucatán Current, which represent waters of the Loop Current and the Gulf of Mexico, silicate content is low, ranging from undetectable to 2 µM from the surface to 200 m depth (Froelich *et al.* 1978). Below this depth it increases to 23-25 µM, which Morrison and Nowlin (1977) and Carder *et al.* (1977) associate with the Antarctic Intermediate Water (500 to 1,000 m). However, Vidal *et al*. (1990) and other authors point out that the maximum levels of silicates in the Gulf originate from the Caribbean Intermediate Water (28 µM) and the upper portion of the North Atlantic Deep Water (16 µM) between 1,000 and 1,100 m depth.

The vertical distribution of silicates depends on the gyres. It increases towards the surface in the cyclonic gyres due to rising of waters that are rich in this nutrient and decreases in the anticyclonic, due to the sinking of the surface layer that is poor in silicates (Fig. 3.13).

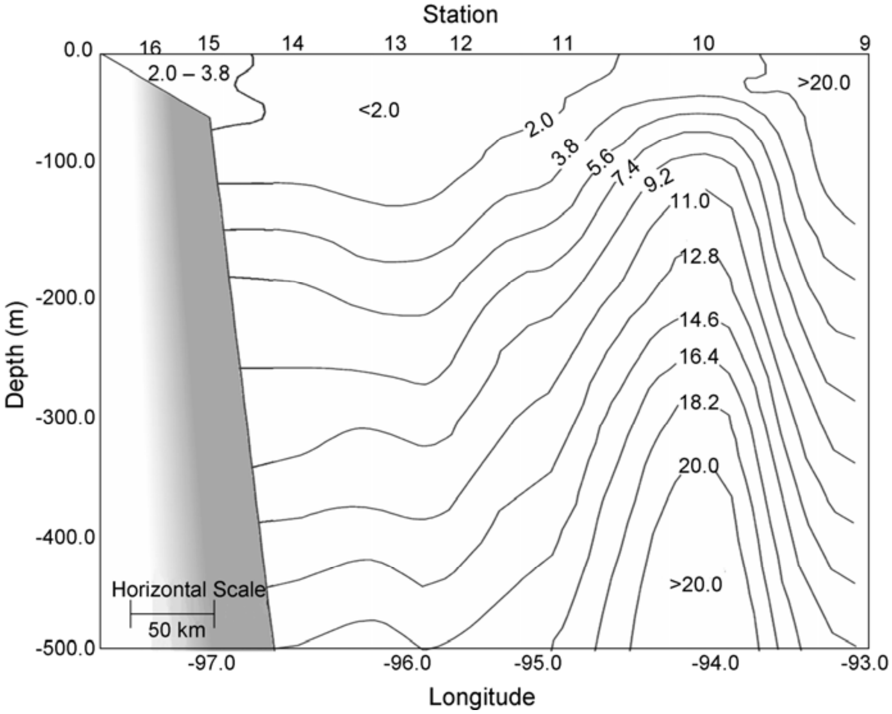


Fig. 3.13. Vertical profile of silicate concentrations (µM) in the cyclonic gyre opposite the Laguna Madre. Redrawn from Vidal *et al.* (1990).

CHLOROPHYLL *A*

The minimum surface content of chlorophyll occurs in the oceanic region inside the north cyclonic gyre, at 0.5 mg/m^3 and a maximum (>3.0 mg/m^3) opposite the mouth of the Rio Grande and the Pánuco, Tuxpan and Cazones rivers. As in the case of nutrients, these maxima are associated with the cyclonic-anticyclonic circulation and the continental river discharge.

Contents of 3.5 mg/m^3 are related to the southern cyclonic circulation, which predominates on the Campeche shelf, and also receives discharges from the Papaloapan, Grijalva and Usumacinta rivers (Vidal *et al.* 1990).

Despite punctual increments of this pigment in cyclonic gyres and coastal areas, the distribution of chlorophyll *a* in the Gulf of Mexico varies spatially and in general exhibits low levels. Satellite images have detected low concentrations in summer (May-July) of <0.06 mg/m^3 with slight increase in winter (December-February) of >0.18 mg/m^3 in the eastern and northeastern Gulf of Mexico. At high sea the concentration of chlorophyll *a* is 0.2 mg/m^3, whilst at the coast it is >0.5 mg/m^3, reaching 5 mg/m^3 in some areas influenced by the input from the Mississippi River, coastal lagoons and cyclonic gyres (Müller-Karger and Walsh 1991). An image of the upwelling in the Yucatán coast with high concentrations of chlorophyll (3 mg/m^3) in April 2000, from SeaWiFS, was interpreted by Aguirre (2002). Similar behavior was observed in October 1979 with an image of the CZCS (Coastal Zone Color Scanner) (Fig. 3.14).

The wide differences in the concentration of chlorophyll *a* may not be due only to the phytoplankton seasonality, but to methodological aspects as well. This is observed in the results obtained by Signoret *et al.* (1998) on the Yucatán shelf, where concentrations of 1.61 mg/m^3 were registered at the surface, and 4.24 mg/m^3 at 20 m depth. This is due to the surfacing of nutrient-rich waters, whilst in the central portion of the Gulf values of 0.04 to 0.07 mg/m^3, typical of oligotrophic seas, were registered, with 0.33 mg/m^3 at 120 m depth, associated with a greater content of nutrients.

Merino-Ibarra (1992) noticed that nitrate and chlorophyll *a* concentration coincided both spatially and temporally, between the upwelling zone (with a maximum of 2 mg/m^3) and the mixed waters (0.25 mg/m^3) (Fig. 3.15).

Walsh *et al.* (1989) used a numerical model to determine that the controlling factor for the seasonal variation of chlorophyll *a* concentration in the waters of the Gulf of Mexico is the depth of the mixing layer and the availability of nutrients. The algae biomass is high when the surface mixing layer is deeper and, as a consequence, the primary productivity in this layer is controlled by the variation in the upward flux of nutrients.

CONCLUSIONS

It is important to point out that the information presented above refers to the global framework of the Gulf of Mexico, and that its coastal zone (ranging from the coastline to the limit of the shelf for the purpose of this paper) can present modifications in the physical and chemical dynamics due to anthropogenic influences, which have been most decisive during the last 20 years.

Given the relative frequency and regularity of the oceanic gyres (cold cyclonic with higher nutrients content in Yucatán, and warm cyclonic-anticyclonic with lower nutrients content opposite the Laguna Madre and Tamaulipas, respectively), and the effect of the dynamic upwelling with greater nutrient content at the Yucatán Peninsula, frequent coastal monitoring is required to register changes in water quality. Monitoring includes physical and chemical parameters (circulation, temperature, nutrients and organic content), as well as hydrocarbons, pesticides and bacteriological parameters opposite the areas of river discharge. This would sustain the application of the Normas Oficiales Mexicana (NOM; Official Mexican Standards) with the support of the Comisión Nacional del Agua (CNA; National Water Commission), the Comisión Federal de Electricidad (CFE; Federal Electricity Comisión), Petróleos Mexicanos

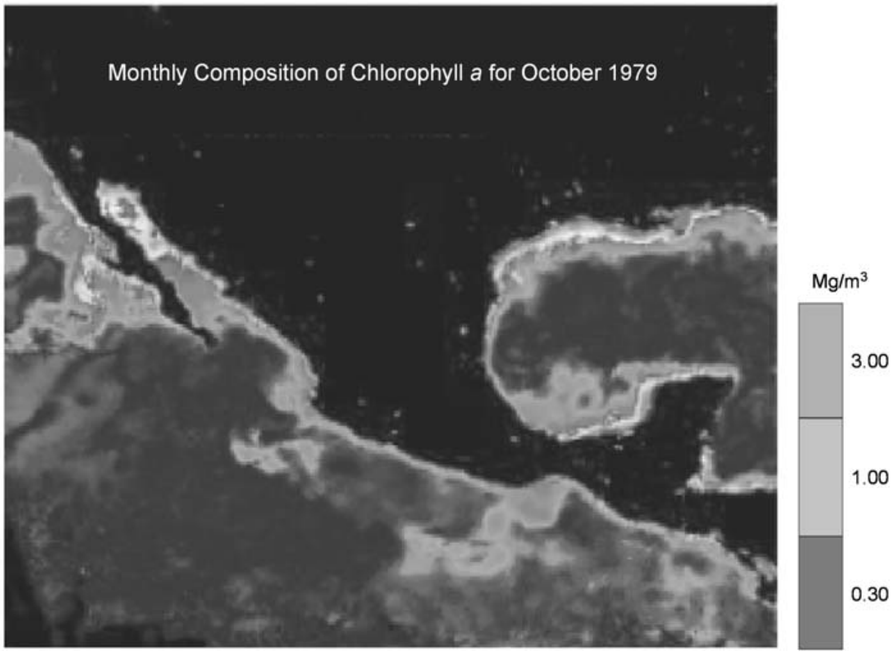


Fig. 3.14. Image of the costal zone color scanner (CZCS) that defines the chlorophyll *a* content in the Gulf of Mexico (Aguirre-Gomez 2002)

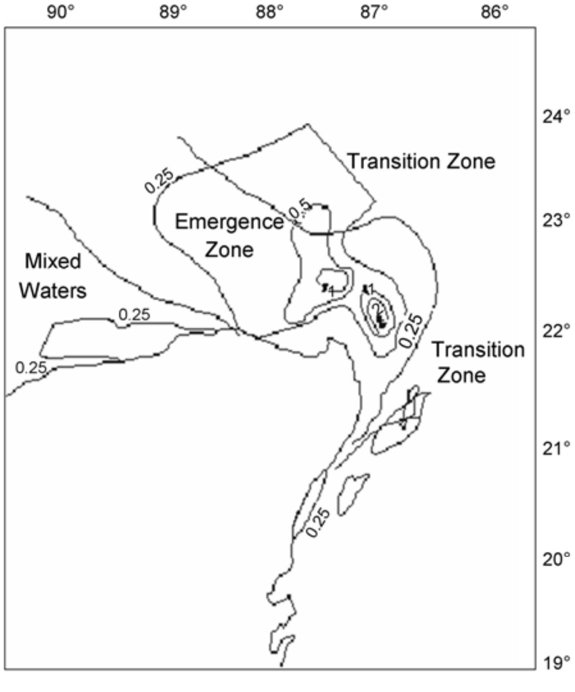


Fig. 3.15. Surface distribution of chlorophyll *a* content (mg/m^3) by zone in the Yucatán shelf. Redrawn from Merino-Ibarra (1992).

(PEMEX; National Mexican Petroleum Company), and the Secretaría de Marina (Secretariat of the Navy). The results would be integrated and managed by the Instituto Nacional de Ecología (INE; National Institute of Ecology), Secretaría del Medio Ambiente y Recursos Naturales (SEMARNAT; Secretariat of Environment and Natural Resources) or an equivalent institution in the future, as well as made available on the worldwide web to allow access for scientific purposes.

LITERATURE CITED

Aguirre, R. 2002. *Los Mares Mexicanos a Través de la Percepción Remota.* Mexico, D.F.: Instituto de Geografía, Universidad Nacional Autónoma de México and Plaza y Valdez. 85 pp.

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.

Bogdanov, D. V. 1969. Some oceanographic features of the Gulf of Mexico and the Caribbean Sea. Pp. 13-35 in A. S. Bogdanov (ed.), *Soviet-Cuban Fishery Research,* Jerusalem: Israel Program for Scientific Translations.

Brooks, D. A., and R. V. Legeckis. 1982. A ship and satellite view of hydrographic features in the western Gulf of Mexico. *Journal of Geophysical Research* 87(C5):4195-4206.

Carder, K. A., R. Fanning , P. Betzer, and V. Maynard. 1977. Dissolved silica and circulation in the Yucatán Strait and deep eastern Gulf of Mexico. *Deep-Sea Research* 24:1149-1160.

De la Lanza Espino, G. 1991. *Oceanografía de los Mares Mexicanos*. Mexico, D.F.: AGT Editor S.A. 569 pp.

Eliott, B. 1979. Anticyclonic Rings and the Energetics of the Circulation of the Gulf of Mexico. Ph.D diss., Texas A&M University, College Station. 188 pp.

______. 1982. Anticyclonic rings in of the Gulf of Mexico. *Journal of Geophysical Research* 12:1292-1309.

El-Sayed, S. Z., W. M. Sackett, L. M. Jeffrey, A. D. Fredericks, R. P. Saunders, G. A. Fryxell, K. A. Steidinges, and S. A. Earle. 1972. Serial atlas of the marine environment. Folio 22 in *Chemistry, Primary Productivity and Benthic algae of the Gulf of Mexico*. New York: American Geographical Society.

Froelich, N. P., K. D. Atwood, and G. S. Giese. 1978. Influence of Amazon River discharge on surface salinity and dissolved silicate concentration in the Caribbean. *Deep-Sea Research* 25:735-744.

Grace, S. F. 1932. The principal diurnal constituent of tidal motion in the Gulf of Mexico. *Monthly Notices of the Royal Astronomical Society of Geophysics Supply* 3(2):70-83.

Instituto Mexicano del Petróleo. 1980. *Informe de los Trabajos Realizados para el Control del Pozo Ixtoc I, el Combate del Derrame de Petróleo y Determinación de sus Efectos sobre el Ambiente Marino*. Programa Coordinado de Estudios Ecológicos en la Sonda de Campeche, México. México, D.F.: Instituto Mexicano del Petróleo. 238 pp.

Kinard, W. F., D. K. Atwood, and G. S. Giese. 1974. Dissolved oxygen as evidence for 18 ºC Sargasso Sea Water in the eastern Caribbean. *Deep- Sea Research* 21:79-82.

Kirwan, A. D., W. J. Merrell, J. K. Lewis, and R. E. Whitaker. 1984. Lagrangian observations of an anticyclonic ring in the western Gulf of Mexico. *Journal of Geophysics Research* 89(C3):3417-3424.

Licea, S., and H. Santoyo. 1991. Algunas características ecológicas del fitoplancton de la región central de la bahía de Campeche. *Anales del Instituto de Ciencias del Mar y Limnología* 18(2):157-167.

Marmer, H. A. 1954. Tides and sea level in the Gulf of Mexico. *Fishery Bulletin of the U.S. Fish and Wildlife Service* 55(89):101-118.

Merino-Ibarra, M. 1983. Estudios Ambientales del Arrecife de Puerto Morelos, Quintana Roo. Informe del Proyecto de Investigación PAMOR. Tesis maestría, Universidad Nacional Autónoma de México, México, D.F. 52 pp.

_______. 1992. Afloramiento en Plataforma de Yucatán; Estructura y Fertilización. Tesis doctoral, Universidad Nacional Autónoma de México, México, D.F. 255 pp.

Metcalf, W. G. 1976. Caribbean-Atlantic exchange through the Anegada-Jungfern passage. *Journal of Geophysics Research* 81:6401-6409.

Molinari, R. L., and J. Morrison. 1988. The separation of the Yucatán Current from the Campeche Bank and intrusion of Loop Current into the Gulf of Mexico. *Journal of Geophysical Research* 93(C9):10645-10654.

Morrison, J. M., and W. D. Nowlin Jr. 1977. Repeated nutrient, oxygen, and density sections through the Loop Current. *Journal of Marine Research* 35:105-128.

Moulin, R. J. 1980. *Observaciones Hidrológicas Frente al Litoral de Tamaulipas en el Golfo de México*. México, D.F,: Secretaría de Marina, Dirección General de Oceanografía. 47 pp.

Müller-Karger, F. E., and J. J.Walsh. 1991. On the seasonal phytoplankton concentration and sea surface as determined by satellites. *Journal of Geophysical Research* 96(C7):12645-12665.

Nowlin, W. D. 1971. Water masses and general circulation of the Gulf of Mexico. *Oceanology* 452:173-178.

——. 1972. Winter circulation and property distributions. Pp. 3-51 in L. R. Capurro and J. Reis (eds.), *Contributions on the Physical Oceanography of the Gulf of Mexico.* Houston, Texas: Gulf Publishing Company.

Nowlin, W. D., and H. J. Mc Lellan. 1967. A characterization of the Gulf of Mexico water in winter. *Journal of Marine Research* 25:29-59.

Pickard, G. L. 1979. *Descriptive Physical Oceanography*, 3rd ed. Oxford: Pergamon Press. 233 pp.

Ponce-Vélez, G., R. Pineda-López, and Y. Pica-Granados. 1991. Oceanografía química. Pp 79-106 in G. De la Lanza Espino G. (ed.), *Oceanografía de Mares Mexicanos.* Mexico, D.F.: AGT Editor.

Reid, R. O., and R. E. Whitaker. 1981. *Numerical Model for Astronomical Tides in the Gulf of Mexico*. Contract Report DACW39-79- C-0074, U.S. Army Corp of Engineers Waterways Experiment Station. College Station, Texas: Texas A&M University, Department of Oceanography. 115 pp.

Schroeder, E., H. Stommel, D. Menzel, and W. Sutcliffe. 1959. Climatic stability of eighteen degree water at Bermuda. *Journal of Geophysics Research* 77:1032-1049.

Secretaría de Marina. 1972a. Informe de Datos Oceanográficos III Crucero VU/71-14. México, D.F.: Instituto Nacional de Pesca and Secretaría de Marina. 160 pp.

_______. 1972b. Informe de datos oceanográficos IV crucero VU/71-20. Mexico, DF, Mexico: Instituto Nacional de Pesca and Secretaría de Marina. 158 pp.

______. 1980. *Contribución al Conocimiento de las Características Fisicoquímicas de las Aguas del Caribe Mexicano: Química del Océano*. México, D.F.: Secretaría de Marina. 58 pp.

______. 2002. *Atlas de Dinámica Costera de la República Mexicana*. México, D.F.: Secretaria de Marina-Armada de México. 223 pp.

Segura,G. J., S. E. Batllori, V. V. Olvera, and R. S. Domínguez. 1982. Productividad primaria en al región sureste del Golfo de México (Mayo, 1982). *Biología Marina* 1(5):237-276.

Signoret, M., C. Bulit, and R. Pérez. 1998. Patrones de distribución de clorofila *a* y producción primaria en aguas del Golfo de México y del Mar Caribe. *Hidrobiológica* 8(2):81-88.

Sterneck, R. 1920. Die Gezeiten der Ozeane. *Sitzungsberichte. Bayeriche Akademie der Wissenschaften zu Muenchen* 129:131-150.

U.S. Department of the Navy (Naval Oceanography), U.S. Dept. of Commerce (Weather Bureau). 1963. *Atlas of Pilot Charts, Central America Water*. Washington, D.C.: U.S. Naval Oceanographic Office, Dept. of the Navy. 16 folded leaves of plates.

Vidal, V. M. V., F. V. Vidal, and O. A. F. Hernández. 1990. *Atlas Oceanográfico del Golfo de México, Volumen III*. Cuernavaca, Morelos, México: Instituto de Investigaciones Eléctricas, Grupo de Estudios Oceanográficos. 586 pp.

______, ______, A. F. Hernández, E. Meza, and L. Zambrano. 1994. Winter water mass distributions in the western Gulf of Mexico affected by a colliding anticyclonic ring. *Journal of Oceanography* 50:55.

______, ______, R. Morales, and J. M. Pérez. 1986b. Hydrographic evidence for the collision of a Loop Current Ring in the western Gulf of Mexico. *Eos Transactions of the American Geophysical Union* 67(44):1049.

______, ______,______, ______, and L. Zambrano. 1986a. Análisis de la campaña oceanográfica Argos 84-1. Informe IIE/13/1926/I 02/P. Cuernavaca, Morelos, México: Instituto de Investigaciones Eléctricas. 340 pp.

______, ______, P. F. Rodríguez, L. Zambrano, J. Portilla, R. Rendón, and B. Jaimes de la Cruz. 1999. Circulación del Golfo de México. *Revista de la Sociedad Mexicana de Historia Natural* 49:1-15.

Walsh, J. L, D. A. Dieterle, M. B. Meyer, and F. E. Müller-Karger. 1989.Nitrogen exchange at the continental margin: A numerical study of the Gulf of Mexico. *Progress in Oceanography* 23:248-301.

Worthington, L.V. 1959. The 18 ºC water in the Sargasso Sea. *Deep-Sea Research* 5:297-305.

Wüst, G. 1963. On the stratification and the circulation in the cold water sphere of the Antillean-Caribbean basins. *Deep-Sea Research* 10:165-187.

_______. 1964. Stratification and the Circulation in the Antillean-Caribbean Basins. Part 1. Irvington, New York: Columbia University Press. 201 pp.

Zettler, B. D., and D. V. Hansen. 1972. Tides in the Gulf of Mexico. Pp. 265-275 in L. R. A. Capurro and J. L. Reid (eds.), *Contributions on the Physical Oceanography of the Gulf of Mexico.* Houston, Texas: Gulf Publishing Company.