Observation of a Distributional Mechanism: Implications in Support of a Kemp's Ridley Pelagic Nursery Hypothesis

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ABSTRACT

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The Gulf of Mexico contains the only known breeding population of Kemp's Ridley Sea Turtles (*Lepidochelys kempi*); the turtles come ashore to nest along a seventeen mile stretch of coastline near the town of Rancho Nuevo in the Tamaulipas state of Mexico. Once the hatchlings leave the nests and enter the water they are not seen again until they migrate into near shore waters as yearlings. Dr. Sneed Collard of the University of West Florida proposed that during this "lost year" the hatchlings could survive as passive drifters within a Gulf of Mexico pelagic nursery. Two Argos-reported surface drifter trajectories are used to support this theory by providing evidence that a passively drifting object can remain within the Gulf of Mexico for periods in excess of a year and are further used to demonstrate an example of the mechanism by which drifting

objects can be transported from one current regime to another. Field observations discussed herein give reasonable evidence that there are episodic physical features in the Gulf interpretable as chaotic transporters of both active swimmers and passive drifters. Case studies of these transport processes shows them capable of providing surface water trajectories consistent with Dr. Collard's pelagic nursery hypothesis.

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I. Introduction

A. Objective

The Gulf of Mexico contains the only known breeding population of Kemp's Ridley sea turtles. Female turtles come ashore in late spring and early summer to lay their eggs on a single nesting beach in the state of Tamaulipas, Mexico. The young hatch two to three months later from June to October and swim out to sea. They are not seen again until they appear as yearlings in nearshore waters and adopt the adult lifestyle of benthic carnivores. Dr. Sneed Collard of the University of West Florida proposed a pelagic nursery theory to explain this "lost year" in the life cycle of the Kemp's Ridley.

Dr. Collard proposed that neonate sea turtles could survive as passive drifters riding the currents of the Gulf of Mexico for a year until they were able to break out of the currents and migrate closer to shore (Collard, 1987). The purpose of this paper is to provide an example that demonstrates it is possible for a neonate Kemp's Ridley to spend an entire year as a passive drifter without being carried out of the Gulf of Mexico. The observations provide examples of physical features that allow them to accomplish this journey. This paper will deal exclusively with surface circulation patterns since hatchling Kemp's Ridley are found only in surface waters.

B. Observational methods

Observations of circulation in the Gulf of Mexico were made using two systems aboard NOAA satellites, the Advanced Very High Resolution Radiometer (AVHRR) and the Argos Data Collection System (DCS). AVHRR infrared images provide visualizations of surface temperature patterns that allow the estimates of circulating water masses and their flow regimes (Vastano and Borders, 1984) within the Gulf of Mexico (Fig. 1, 2 and 9). The dark masses are warm bodies of water while cool water masses are shown in shades of grey. The DCS utilized Far Horizon Drifters (FHDA-1) manufactured by Horizon Marine (Fig. 3) released at various locations in the Gulf of Mexico. These drifters were drogued to surface layer depths and moved passively with the water masses that contained them. Their locations were received by the polar-orbiting satellites approximately eight times per day. The path of the drifters could be tracked from these locations over the entire Gulf of Mexico (Fig. 4 and 5).

C. Biological Background

The Kemp's Ridley, *Lepidochelys kempi*, (Fig. 6) is the smallest of the sea turtles native to the Gulf of Mexico (Márquez). In the adult, the greenish brown carapace is rounded with the width being more than 90% of the length (Márquez). Size ranges from 60 to 70 cm in length and weights from 35 to 45 kg with females weighing in slightly heavier than the males. The hatchling's carapace is longer than it is wide with the measurements becoming more similar as the turtle matures. At hatching, the turtles are dark grey and black when wet but quickly develop a light undershell (Márquez).

The Kemp's Ridley population is restricted to the Northwest Atlantic, the Gulf of Mexico in particular. A population of mostly immature turtles exists along the eastern coast of the United States but it is not known if they remain there permanently or migrate back to the Gulf of Mexico. A few records of Kemp's Ridley found in Europe and North Africa are of young turtles swept across the Atlantic in the Gulf Stream. It is highly unlikely these individuals ever make it back to the breeding population in the Gulf of Mexico and no record has been found of a permanent population on the east side of the Atlantic. The breeding population is found in the Gulf of Mexico where females nest at only one known site in the Tamaulipas state of Mexico near the town of Rancho Nuevo (Márquez).

Yearling and adult turtles live in shallow, near shore waters where they dive for the crustaceans, gastropods and clams (Fuller, 1978) that make up the bulk of their diet. Feeding grounds are found on the north and south coasts of the Gulf of Mexico concentrated in the north around the mouth of the Mississippi and in the Florida Bay and to the south around the Campeche Sound (Márquez).

Maturity is reached at six to seven years of age. The adults migrate yearly to a long sand beach (23°18'10" to 23°10'00" north, 97°45'40" to 97°45'30" west) (Fig. 7). The females come ashore in large groups or arribazones (also arribadas) from April to August (Márquez). They are the only know species of sea turtle to nest exclusively during the day (Fuller, 1978). The nests contain an average of 105 eggs. Though females can nest more than once in a season, less than 30% of the them do so and around 850 nests are laid each year (Márquez).

Incubation takes 50 to 70 days. Not all nests laid at the same time will hatch together, though within a nest all of the hatchlings emerge at once. Because of this and a small number of solitary females that nest outside of the arribazones, there is a fairly constant number of hatchlings entering the water from June through October. The nests are raided by a variety of predators including coyotes, raccoons, skunks, ants, and ghost crabs. The hatchlings leave the nest during the cooler parts of the day to avoid overheating on the way to the ocean as the sand can reach 45°C during the day. The turtles race towards the surf in an instinctive attempt to avoid predation on their way to the water. This is the most dangerous part of the life cycle for Kemp's Ridley since predators are attracted visually to the running turtles. Ghost crabs, coyotes, raccoons, skunks, and badgers prey on the hatchlings as well as birds such as buzzards, grackles and hawks. From the time the nests are laid until the hatchlings first reach the water the estimated survivorship is 0.609 (60.9%) (Márquez).

Once the turtles have reached the water they are vulnerable at the surface to gulls, terns and frigate birds and underwater to sharks, barracudas, yellow tail and other medium to big predatory fish. The hatchlings enter the water and swim towards and through the line of surf and out to sea. This swim frenzy may last for hours and carries the hatchling far away from the beach to minimize the possibility of being washed back to shore. It is not known where the hatchlings go from there until they appear as yearlings along the Gulf and western Atlantic coasts

(Márquez).

Survivorship to adulthood, seven years, has been estimated at anywhere from two per every thousand eggs laid (0.2%) (Collard, 1987) to 0.0572 (5.72%) (Márquez). Since there is no fishery and adult males are never observed on shore, population estimates must be based on the number of females that come ashore to nest. The proportion of males to females in the adult population is also not known. The current population is estimated to contain less than one thousand breeding females (Márquez).

The distribution of hatchling Kemp's Ridley is unknown once they leave the nesting beach. Due to their small size, on average 44 cm in length, 38 in width, weighing 17 grams, and their dark coloration, the hatchlings are very difficult to observe in the wild. Hatchling sea turtles are able to swim at an estimated one knot during the swim frenzy (Collard, 1987) seen immediately after hatching. But due to their size, they can be considered passive drifters, unable to voluntarily leave the currents in which they become embedded. There is almost no data on their distribution until they have grown sufficiently to stem the currents and enter the near shore environment along the Gulf coast and west Atlantic coast as yearlings (Márquez). It is this so called "lost year" that will be dealt with in this paper.

D. Pelagic Nursery Hypothesis

Sneed Collard of the University of West Florida in "Review of Oceanographic features relating to neonate sea turtle distribution and dispersal in the pelagic environment: Kemp's Ridley (*Lepidochelys kempi*) in the Gulf of Mexico" introduced the theory of a pelagic nursery. The relation of turtles to physical features was made to explain the disappearance of hatchling Kemp's Ridley during the "lost year" between hatching and their appearance as coastal yearlings. Dr. Collard proposed that once hatchlings leave the natal beach they could survive and grow to maturity as passive drifters, essentially plankton, in the currents of the Gulf of Mexico. In his scheme patches of Sargassum would provide protection from predators as well as a source of food. Thus the turtles would not be observed at any near shore locations, which is the case, until they had reached a size to be able to break out of the Gulf currents and enter the near shore waters in which the adults are found (Collard, 1987).

Once within the Sargassum beds, the hatchlings could prey on many of the species that live on the weed. Captive Kemp's Ridley hatchlings are nutritional generalists and have been observed to grow well on a wide variety of food sources including lettuce, chopped fish and shrimp. It is not known whether Kemp's Ridley can metabolize Sargassum itself though the length of their gut implies that they are herbivores after birth. The surface waters of the Gulf are inhabited by a wide variety of gelatinous animals (ctenophores, jellyfish, salps, etc.) that could be eaten by hatchling sea turtles. Marine snow, the filtering nets of pteropods and other types of zooplankton, could also provide a food source for hatchlings. Other species of sea turtle such as the Green and Loggerhead have been observed to feed on gelatinous animals and jellyfish after hatching. There is no reason to believe that the Kemp's Ridley hatchlings should pursue a different strategy (Collard, 1987).

The physical processes that cause the convergence of Sargassum and other food sources for the neonate turtles (down-welling, front formation, the concentration of floating material in eddies, etc.) produce floating patches that would also serve to concentrate passively drifting Kemp's Ridley hatchlings. This alleviates one of the largest problems facing the hatchlings: finding food. By simply drifting passively a good proportion of the hatchlings would come into contact with an adequate amount of food. But there are no strategies that do not include risks and drifting passively also increases the risk of coming into contact with tar balls and plastic debris which, if ingested, can kill the turtles. The convergence process could also serve to congregate hatchlings for predators if there were enough neonates in the area (Collard, 1987).

A major problem facing the hatchlings is the possibility of being swept out of the Gulf of Mexico and embedded in the Gulf Stream. Records of Kemp's Ridley yearlings found in Europe and Africa shows that this can occur. The placement of the nesting beach in relation to the circulation patterns of the Gulf could minimize this risk. There is a small expatriot population of Kemp's Ridley on the East coast of the United States, especially noted in the Long Island Sound. However, their relationship with the Gulf of Mexico population has not been established. The individuals swept across the Atlantic to Europe are almost certainly lost to the breeding population (Collard, 1987).

E. Physical Background

The Gulf of Mexico is characterized by significant physical variability that is often noted through surface water expressions of episodic events. This turbulent aspect can override and thereby disrupt mean background flow patterns. Such events are responses to oceanic, atmospheric, riverine or estuarine (Vastano et al., 1995) forcing. These are often inferred as turbulent features in infrared satellite images of surface temperature patterns around the Gulf of Mexico (Vastano, Shaar and Barron, 1994). The satellite infrared image observation and estimation of highly variable current speeds has been validated in experiments comparing satellite estimates and Argos drifter tracks (Vastano and Barron, 1994). Many large scale semi-permanent physical features exist in the Gulf. They can be highly variable in geographic position, water mass characteristics, current strength and life span. A summary of particularly pertinent physical features follows.

1. The Loop Current

The most energetic features are often the Loop Current and its derivatives. The Loop Current arises in the northwestern Caribbean Sea as the Yucatan Current and enters the Gulf through the Yucatan Straits. The current can be observed in satellite images as a large hair-pin shaped loop or meander of relatively warm, or dark, water that extends northward off the west coast of Florida (Fig. 1). Transport through the Yucatan Straits can reach as high as 25 Sv (25×10^6 m^3 s^{-1} or about 25 million bathtubs of water per second) and flow through the Florida Strait can exceed 30 Sv (Anderson and Corry, 1985) with an average velocity of 25 cm s^{-1}.

2. Loop Current Eddies

When the northern aspect of the loop reaches beyond 26°N, current instabilities and topographic interactions can sometimes cause an anti-cyclonic eddy or circular ring currents to pinch off (Fig. 2). The normal path or trajectory of such an eddy is a slow drift westward (Cooper and Joyce, 1990). Observations have shown that this can occur once every 8.5 months on average (De la Cerda, 1993). During their lifetime, the rings travel westward at approximately 5 km d^{-1} with a 55% decrease in surface area over 150 days (Cooper and Joyce, 1990). The rings drift and mix with background waters until they interact with the continental shelf and dissipate, anywhere from the Texas-Louisiana coast to the southern regions of Mexico (Cooper and Joyce, 1990). These warm-core, anti-cyclonic (clockwise rotating) rings contain diffused high salinity Caribbean waters and serve to transport energy, momentum and organisms native to the Caribbean region toward the western Gulf of Mexico (Cooper and Joyce, 1990). They are a significant cause of turbulence and current fluctuation in all areas of the Gulf (Brooks, 1984).

3. Texas-Louisiana Shelf Circulation

Another semi-permanent feature found over the Texas-Louisiana shelf is a cyclonic gyre which extends from Brownsville to around 90° west (Cochrane and Kelly, 1986). During most of the year a combination of wind, oceanic features, river and estuary contrive to produce nearshore currents southwestward along the shelf, motion northeast and then eastward along the Shelf's edge, and westward movement along the Louisiana and Texas coasts to close the circulation (Fig. 12) (Vastano et al., 1995). Motion in response to external forcing can also produce seaward flow across the shelf and central portion of the shelf gyre. From September to June, the coastal boundaries, the nearshore southwestward current off Texas and north-northeasterly current from Mexico at the shelf break's Brownsville Front (Vastano and Barron, 1994) are factors that serve to form the western limbs of the cyclonic gyre (Cochrane and Kelly, 1986). July and August are accompanied by persistent yet slower shelf surface flow to the northeast under the direct influence of prevailing southeast to south winds (Cochrane and Kelly, 1986). In this circumstance, the cyclonic gyre on the shelf weakens and its southerly penetration along Padre Island and the adjacent shelf is foreshortened. A mean surface flow of approximately 25 - 35 cm s^{-1} has been observed by

Argos drifters along the northwest portion of the Shelf's cyclonic gyre (Cochrane and Kelly, 1986).

Synoptic realizations show these currents to be highly variable at twenty-four hour time scales as they reach speeds of three to four times the mean. Since the transport of this gyre is low and in relatively shallow water, it can be easily disrupted by transient episodic events (Vastano et al., 1995, Vastano, Shaar and Barron, 1994) such as the seaward passage of an atmospheric front or the movement of a Loop Current eddy along the outer shelf edge. Within any given month, intervals of complete flow reversal relative to the expected mean can be accomplished by temporary breakdowns of the normally ordered current patterns into turbulent, chaotic mixing regimes (Shaar, 1994) (Fig. 8).

4. The Texas Plume

In its many manifestations, the Texas Plume is a transient meander event along the edge of the Texas continental shelf that represents a major shelf-slope water exchange process (Barron and Vastano, 1994). The fundamental appearance of the Plume's temperature pattern suggests origins in a confluence of northern and southern waters. The southern component arises along the western side of the Bay of Campeche and intrudes northward, usually offshore, along the Shelf edge from the latitude of Brownsville (Barron and Vastano, 1994) (Fig. 9). This northward regime can meet the southwesterly nearshore flow along the Texas coast as the shelf width narrows to the south and the shoreline of lower Padre Island reaches south-southeasterly forming the southern boundary of the Texas Bight. Here, the confluence of the two near-opposing currents occurs in a seaward juncture just shoreward of the shelf edge (Barron and Vastano, 1994). The result is often an offshore reversal of the northern component, and its entrainment and mixing with the shelfside portion of its southern counterpart, and the formation of the Brownsville Front along the Shelf Edge (Fig. 9 and 14). The front and flow follow the shelf's edge northeastward and then eastward and the Plume develops episodically as an accelerating flow seaward, off the shelf, between 27°40' north, 95°40' west, a topographical break in the shelf edge bottom topography and the Flower Garden Reefs, 27°53' north, 93°45" west. The southeastward extension and its reversal to the northward forms the Texas Plume that returns to eastward flow along the shelf edge south of Louisiana.

As Plumes evolve they have the potential to concentrate floating material carried out in coastal waters from Texas to Mexico. The Plumes form and dissipate over month or longer intervals, and have narrow, geographically stable inner regions (Vastano et al., 1994) that can evolve slow counterclockwise motion. While Texas Plumes can contain central confined regions of low exchange with their environments, eddies formed along the flow instabilities on the seaward side of the Brownsville Front (Vastano, Shaar and Barron, 1994) can be advected rapidly along its periphery. In this manner, smaller counterclockwise-rotating eddies transport waters along the Plume, eventually reaching its southeastward extremity, and sometimes fold back northwestward to become a transient part of the plume itself. Similar plumes can be observed along the Tamaulipas coasts of Mexico. Sequences of these plumes coexists extending along the edge of the western Gulf of Mexico continental shelf that is, in a converse manner, reminiscent of offshore filaments of the California Current System.

The Texas Plume's offshelf flow originates on the Brownsville Front and moves waters seaward, forming the western side or boundary of a warm oceanic water mass over the Texas Continental Slope. The eastern boundary of the oceanic water is the Brownsville Front itself flowing northward along the shelf break. This particular water mass is thus enclosed to the west, north and south and is singled out for identification for the role it plays in the case study to follow. It is here after referred to "eddy" 2 (Fig. 14).

Instabilities along the cold Brownsville Front and around the warm oceanic water mass often result in the formation of small eddy features. These eddies advect along the Front and can be transported off the shelf and down into the Plume itself. They offer a smaller scale means for turbulent transport of surface material by "background" flow regimes of the semi-permanent feature. This, much in the manner of the poem that expresses the thought: "fleas have little fleas upon their backs."

The region in the throat of the Plume, often found in the vicinity of the Flower Gardens, is juxtaposed between the southerly and northerly motion associated with the Plume and has a slow, counterclockwise flow within. For the case study to come this shelf water in the throat of the Plume is called eddy 1 (Fig. 14).

5. The Bay of Campeche Cyclone

De la Cerda provided strong observational evidence of a semi-permanent cyclonic feature in the southern reaches of the bay of Campeche (De la Cerda, 1993) (Fig. 10). This cyclonic gyre is partially induced by surface stress associated with the rotating component of winds over the Bay (De la Cerda, 1993). No significant translation of this feature has been observed, implying a stable geographical location owed to strong frictional interaction with bottom topography. The cyclone has been observed in place at all times of the year but is occasionally reduced in size by the approach of and subsequent interaction with anti-cyclonic eddies shed by the Loop current (De la Cerda, 1993).

6. Mexican Coastal Circulation

A similar semi-permanent anti-cyclonic gyre can also be observed along the coast of Mexico from around 21° north to the southernmost extent of the gyre on the Texas shelf (De la Cerda, 1993). One result of interaction of the Texas coastal cyclonic gyre and this anti-cyclonic gyre along the Mexican coast can be transient plumes of shelf and coastal water that are forced out into the Gulf of Mexico and disintegrate into smaller eddies in the same manner as the Texas Plume.

These surface phenomena, described in terms of their surface appearance, are some of the turbulent semi-permanent events that make up the major flow patterns in the Gulf of Mexico pertinent to distribution of surface waters and material. It is important to keep in mind that, at any given time, only a few or none of these pattern elements may be present. As the semi-permanent features are generated and interact with established currents local flow patterns can be completely disrupted. On a larger scale all the circulation patterns in the Gulf influence one another; it is this dynamic interaction of turbulent systems that allows the transport of water and floating material from one current regime to another.

These episodic turbulent processes provide a mechanism for the transfer of floating objects between current system regimes. Chaotic exchanges of water and momentum occur at the shifting boundaries of circulation regimes and represent very effective means of oceanic mixing and redistribution (Wiggens, 1992). Observational programs studying the Gulf of Mexico in general and the western Gulf in particular have shown that exchange processes are prevalent at physical scales from days and kilometers to months and hundreds of kilometers.

II. Drifter Data

Several drifters were deployed in the fall of 1992 along the Texas-Louisiana coast. The two drifters that will be dealt with in this study were launched by Texas A&M University, drifter 5545 of the Texas Flow Program (TEXFLEX), and the Texas-Louisiana Shelf Circulation Program (LATEX) drifter, 2447.

A. Drifter 5545

Drifter 5545 was deployed in the Galveston lightering region on October 10, 1992 at 93°00' west and 95°30' north (Fig. 4) and was drogued to a depth of 2.7 meters. It was carried by a variety of current regimes around the Gulf of Mexico for over a year before ceasing radio transmissions northwest of Yucatan Peninsula. The drifter deployed at approximately the time that hatchlings would be entering the ocean. The drifter was retained in a nearshore coastal jet known as the Texas Current which moved quickly along the Brownsville Front (Barron and Vastano, 1994) southward, down the coast. A seaward movement off Padre Island caused entrainment of the Texas Current waters with flow up the coast from Mexico. The drifter then moved along the Brownsville Front (Barron and Vastano, 1993) to the area of the Flower Garden Reefs where, for five weeks, it slowly described a closed path bounded by 95.2° to 94° west and 28.2° to 27.6° north. At the end of this time the drifter was caught in a sub-mesoscale eddy associated with the Texas Plume that translated southeastward to the vicinity of the Loop Current. Under the influence of the hurricane that passed though the region on March 12, 1993 the drifter was transported southeastward into the area of the continental slope adjacent to the Campeche Bank. The drifter then interacted with an anti-cyclonic cell which caused northwestward movement and eventually resulted in the association of the drifter with several mesoscale and sub-mesoscale eddies south and east of the Louisiana coast. It is notable that at some points in the fall of 1993 the drifter was embedded in a sub-mesoscale eddy that was itself under the influence of a mesoscale eddy translating slowly southward. The drifter went off the air in the area of the Campeche Bank over a year after it was launched.

During the year that it was deployed, the drifter remained within the Gulf of Mexico. It was transported off the Texas-Louisiana shelf and thereafter remained in open waters until it stopped transmission in November of 1993. When the drifter was found washed ashore near Brownsville three months later the drogue was still attached indicating that it had remained within its targeted waters for the entire time it was deployed.

B. Drifter 2447

LATEX drifter 2447 was deployed on August 4, 1992 at 92.000° west, 27.997° north drogued to 9 meters. The drifter remained in the northwestern Gulf of Mexico until it was captured on February 9, 1993 (Fig. 5). After being transported off the shelf early in the track the drifter was caught in a large anti-cyclonic feature confined to an area roughly defined by the shelf break and the bottom of the slope. The Brownsville Front and the Texas Plume induced the clockwise circulation pattern over the western portion of the Texas slope that contained drifter 2447 (Fig. 14).

C. Flow Within a Turbulent Event

The drifter trajectories from November 23 to January 20 show some interesting features. From the 23 of November to the 27 of December, 1993 drifter 5545 was trapped in a small area 95.2° to 94° west and 28.2° to 27.6° north. Shaar (1994) discussed an area of stagnation that existed on the shelf break at this location which will be addressed in more detail in another section.

After drifter 5545 left the quiescent region it moved off the shelf in an eddy that translated southeastward at approximately 7 cm/sec. At the same time drifter 5545 was contained in the stagnation zone and eventually transported off the shelf while another drifter, Latex drifter 2447, was moving over the same area (Fig. 11). Drifter 2447 was held in a larger anti-cyclonic motion induced by oceanic forces interacting with the slope, "eddy" 2 (Fig 14). The smaller eddy that contained the TEXFLEX drifter (eddy 1) passed to the east of "eddy" 2 as it traveled southward off the shelf.

The two drifters remained an average of 200 km apart over the period from late December to late January. They passed over the same areas of the slope and were effected by the same large scale current pattern, the Texas coastal gyre under the effect of the water moving up the coast from Mexico, but were contained in different aspects of that event. Despite their close proximity to one another the drifters were contained in two different water masses within the system and ended up in vastly different parts of the Gulf of Mexico. Drifter 2447 which was embedded in "eddy" 2 over the Texas slope and was transported to the western Gulf of Mexico where it was picked up a few months later. Drifter 5545 that was contained in the stagnation zone at the neck of the Texas Plume and then transported off the shelf by the Plume in a smaller feature eddy 1. Eddy 1 though it interacted with the belly of the Plume was not caught in the quiescent interior of the belly (Fig. 9) and moved out into the Gulf. Drifter 5545 ended up in the central and southern Gulf where it remained for the following year.

III. Discussion

A. Switching Mechanism

The drifter trajectories for the late fall and early winter of 1992 through 1993 demonstrate how passively drifting objects only a small geographical distance apart can become embedded in vastly different aspects of circulation patterns. As hatchling Kemp's Ridleys leave the nesting beach they can trapped in and distributed by the same kinds of turbulent systems.

Over the course of the hatching season very different circulation systems are present offshore at different times. When the Brownsville Front has been formed along the shelf instabilities in the interaction between the current regimes produce eddies that move northwards along its periphery. This provides a mechanism for the transport of passively drifting turtles from Mexican coastal waters up the coast and into the area where the Texas Plume is formed. Changes in these prevailing patterns can take place over a period of days, separating even turtles that hatched at similar times. In addition to this several eddies could be present at any given time, the number of turtles embedded in any one of them would depend on the exact circumstance of weather and currents at the time of hatching. Once the hatchlings were within the circulation systems the turbulent nature of the flow would provide a mechanism of switching between systems as seen in eddy 1 which carried drifter 5545 across the Gulf. It is not necessary for the adult turtles to nest in a wide variety of locations around the Gulf to insure a wide distribution of young. The turbulence due to the episodic events inherent to Gulf of Mexico would insure that the hatchlings were spread over a wide area.

The eddy formation associated with the interaction of these water masses is especially significant in this case as eddies serve to concentrate floating organisms. Young turtles and the Sargassum that they are though to inhabit would be brought into close proximity; this would provide a renewed source of food for the hatchlings. Switching events would thus be extremely beneficial to neonate sea turtles.

B. The Stagnation Zone

Shaar (1994) discussed a semi-permanent area of stagnation that existed on the Texas shelf break within an area roughly 95° to 94° west and 28.2° to 27.6° north during November and December of 1992. When correlated with the seasonal mean flow patterns for the late fall, this area is found to be within the Texas-Louisiana shelf gyre (Fig. 12 and 13) (Vastano, 1994). Thus the conditions that caused this stagnation zone apparently are present consistently from year to year though the location of the stagnation zone could vary with varying current conditions. The Flower Garden Reefs are located near the area in which the drifter was retained, further implying that the stagnation zone is a consistent phenomena. The organic material that would be concentrated on a regular basis in the stagnation zone would encourage the development of the type of enhanced bottom community seen in the reefs.

If such periodic and consistent stagnation zones exist in other areas of the Gulf of Mexico they would be important feeding grounds for pelagic creatures such as sea turtle hatchlings. The neonates would be concentrated in these areas by the same mechanisms that concentrate their food, planktonic animals. Such stagnation zones could exist, unobserved, all along the self break. If so, they play a vial role in concentrating food and shelter for neonate sea turtles.

C. Retention of hatchlings within the Gulf of Mexico

It is of great importance that hatchling Kemp's Ridleys stay within the Gulf of Mexico during their year as passive drifters. Observations of Kemp's Ridley yearlings in waters off Europe and Africa demonstrate the risk to the hatchlings of becoming embedded in the Loop Current which merges with the Gulf Stream once it exits the Florida Straits. It is highly unlikely that these individuals ever find their way back to the breeding population in the Gulf of Mexico. A similar population of young animals can be found along the eastern coast of the United States. It is not know weather or how these animals interact with the Gulf of Mexico population but their uniformly young age (for the most part immature adults less than seven years old) (Márquez) (Collard, 1987) suggests that they are, in some way, able to return to the Gulf as adults.

On the whole, transport of young out of the Gulf of Mexico is the equivalent of the death of the transported turtles with respect to the rest of the breeding population since the turtles transported out of the Gulf are never able to breed and reproduce. The Kemp's Ridley, therefore, depends on the fact that it is possible, and indeed likely, that a significant number of the hatchlings will remain with the Gulf until they are strong enough to stem the current as yearlings.

The track of drifter 5545 shows the movement of a completely passive drifter that remained within the Gulf for over a year. The interaction between turbulent current regimes made it possible for the drifter to be transported across the Gulf several times without being caught in the Loop Current.

D. Recruitment

To insure the continuation of the Kemp's Ridley population enough young turtles must be recruited into the breeding age group (seven years of age and above) each year to replace those lost to old age, disease or accident. Since there is no longer a Kemp's Ridley fishery, the rate of recruitment must be measured by the numbers of adult females that return to the beach at Rancho Nuevo to nest. The size of the male population is unknown as is the relative number of males to females. The recruitment rate for females to age seven has been estimated to be from 0.2% (Collard, 1987) to 5.72% (Márquez). Therefore the vast majority of eggs laid and neonates hatched do not survive to adulthood.

Around 100,000 eggs are laid each year; if even a quarter of these were to survive to sexual maturity the existing Kemp's Ridley population would more than double. The species relies on the high number of young produced to insure that a few, enough to support the population, will survive to maturity. Only a very few, lucky turtles will survive the high rates of predation, find enough to eat and avoid being carried back to shore or out into the Atlantic. Thousands of hatchlings will die during their first year but since there are thousands produced enough survive and enter the adult population to insure the continuance of the species.

Though there is no parental care of the young past nesting, the Kemp's Ridley has evolved several strategies for insuring that each year class of hatchlings has the best possible chances for a significant number to survive to adulthood. Some of the major obstacles facing neonates are: high rates of predation, difficulty in finding food, and the risk of being carried out of the Gulf and away from the breeding population. High rates of predation and competition for food can be reduced by dispersing the hatchlings widely over the Gulf. To avoid a large number of hatchlings being transported into the Atlantic the Kemp's Ridley may use the location of their main nesting beach reduce that risk. Dr. Collard (1987) proposed a type of "bet hedging" practiced by the Kemp's Ridley whereby the location and timing of nesting corresponded with the most favorable current conditions.

Kemp's Ridley come ashore to nest primarily in large groups over a period of several months from April to August. Not all nests laid by these groups, or arribazones, will hatch at the same time and there is a small amount of nesting outside the arribazones. As a result hatchlings enter the water at a fairly steady rate from June through October. By staggering the hatching of nests there is never an excessive number of neonates on the beach at one time, a condition that slightly reduces the risk posed by predators. This staggered hatching also insures that a steady stream in neonates will be entering the coastal circulation patterns during these months. In the absence of any way to predict what the currents will be like on small, hour to day and meter to kilometer, scale a steady flow of young off shore insures that at least some will become embedded in favorable current patterns.

Once the turtles have moved out to sea the episodic turbulent events characteristic of the Gulf of Mexico are vital to their survival. As the hatchlings leave the nesting beach they become embedded in one of the flow patterns that can intrude into the waters off Rancho Nuevo. The hatchlings are, for all practical purposes, passive drifters. If all of the approximately 60,000 hatchlings which reach the water every year were to remain within the area adjacent to the nesting beach survivorship to the end of the first year would be drastically reduced. Not only would there be increased competition for food but the predation rate would be higher due to the increased concentration of hatchlings.

In addition the chances of a single event adversely effecting the whole population of young is tremendously increased if they are contained in a small area. The forcing of surface waters onto shore during a storm could eliminate most of a year class if they were restricted to a small area. The periodic turbulence associated with current patterns in the Gulf of Mexico provides the mechanism to transfer hatchlings from one circulation pattern to another. In this way the hatchlings are spread out over the entire Gulf of Mexico. The wider the area that the hatchlings can be distributed to, within the Gulf, the better the chances of a large yearling population.

E. Nesting Beach Location

The location of the nesting beach provides an advantage to young turtles. The Kemp's Ridley has only one known nesting beach near the town of Rancho Nuevo in the state of Tamaulipas in Mexico (Fig. 7). This stretch of coast line lies within the areas influenced by two major current patterns in the Gulf of Mexico: the cyclonic gyre over the Texas shelf and the anti-cyclonic gyre over the Mexican shelf south of Brownsville. When these two circulation patterns interact with one another or a Loop Current eddy they produce an off shore plume that carries coastal surface water out into the Gulf of Mexico. The nesting beach is ideally geographically situated to afford the hatchling's escape offshore and away from the nesting beach. Hatchlings could be also become imbedded in either one of the gyres themselves and carried away from the nesting beach in that manner.

The location of the nesting beach at the far western end of the Gulf of Mexico places the hatchlings as far as possible from the Loop Current which would carry them out of the Gulf and into the Atlantic ocean. The possibility of young being carried permanently out of the Gulf provides selective pressure for increased nesting at beaches that would reduce, as much as possible, this type of transport.

The Kemp's Ridley population has declined dramatically over the past century from estimates of around 40,000 nesting females in the 1940's (Márquez) to around 1000 today (Collard, 1987). It is highly unlikely that when the population was higher there was only one nesting beach. Smaller nesting locations were probably located around the Gulf of Mexico though the Rancho Nuevo beach would have been among the largest. But as the population decreased the beach that was placed optimally to take advantage of current patterns was the one that remained in used as the others were abandoned or the sub-populations that nested in them were wiped out.

Because the Kemp's Ridley utilizes the turbulent, chaotic events present in the Gulf of Mexico it is impossible, at hatching, to determine which of the young is mostly likely to survive to the end of their first year. The addition of this random factor in neonate survival implies that the stronger, larger and "better suited" hatchlings are not always the ones that survive to adulthood. Rather the characteristic that is selected for is the memory in the turtles themselves of the nesting beach that the majority of the yearlings were hatched at. This would be the nesting beach that was situated most favorably to take advantage of off shore circulation patterns. Over the course of many generations the nesting beaches with the most favorable current conditions during the hatching season would be used to a much greater degree as previous generation returned there to nest and the circulation patterns in turn generated more adults that remembered that beach.

IV. Summary and Conclusions

The purpose of this paper has been to demonstrate that it is possible for neonate Kemp's Ridley to spend an entire year as passive drifters without a significant proportion of the population being carried out of the Gulf of Mexico and to show an example of an aspect of the mechanism that make such a journey possible. The Gulf of Mexico is dominated by turbulent, episodic events which can disrupt regional low energy semi-permanent circulation patterns. These turbulent event can be generated in response to riverine, estuarine, oceanic or atmospheric forcing or by a combination causes (Vastano et al., 1995). During these episodes large scale mixing and turbulent diffusion between water masses serve to transport floating communities (including those containing Kemp's Ridley hatchlings) into new areas controlled by different mean current patterns. In this way neonate sea turtles are transported from one circulation feature to another and eventually to all areas of the Gulf of Mexico.

The major circulation patterns of the Gulf of Mexico include the cyclonic eddy confined to the Texas-Louisiana shelf, the coastal plumes formed by the interaction of circulation systems, the anti-cyclonic eddy along the eastern Gulf coast of Mexico, the Bay of Campeche cyclone, the

Loop current and the warm core anti-cyclonic eddies that pinch off from it and translate westward across the Gulf. These phenomena form a mean pattern of loops and gyres which neonate sea turtles could ride in for over a year. The transport of hatchlings into and between these would be accomplished by the episodic turbulent features of the Gulf of Mexico. All of these circulation patterns would tend to retain floating turtles within the Gulf of Mexico with the exception of the Loop Current. Through the shedding of warm core eddies by the Loop Current could serve as a mechanism for transporting some of the hatchlings trapped within the current back to the western Gulf of Mexico.

The vast majority of hatchlings in any given year meet with unfavorable current conditions, lack of sufficient food or fall prey to a variety of predators. The location of the nesting beach in relation to the coastal circulation patterns aids the hatchlings by distributing them widely over the Gulf and giving them a starting point as far from the Loop Current as possible. Every year enough of the young are able to find sufficient food and avoid transport into the Atlantic to maintain the population using both the mean and turbulent circulation patterns of Gulf itself as a pelagic nursery.

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Fig. 14 A schematic diagram of physical features in the northwest Gulf of Mexico that are significant for the case study. (BF: Brownsville Front)

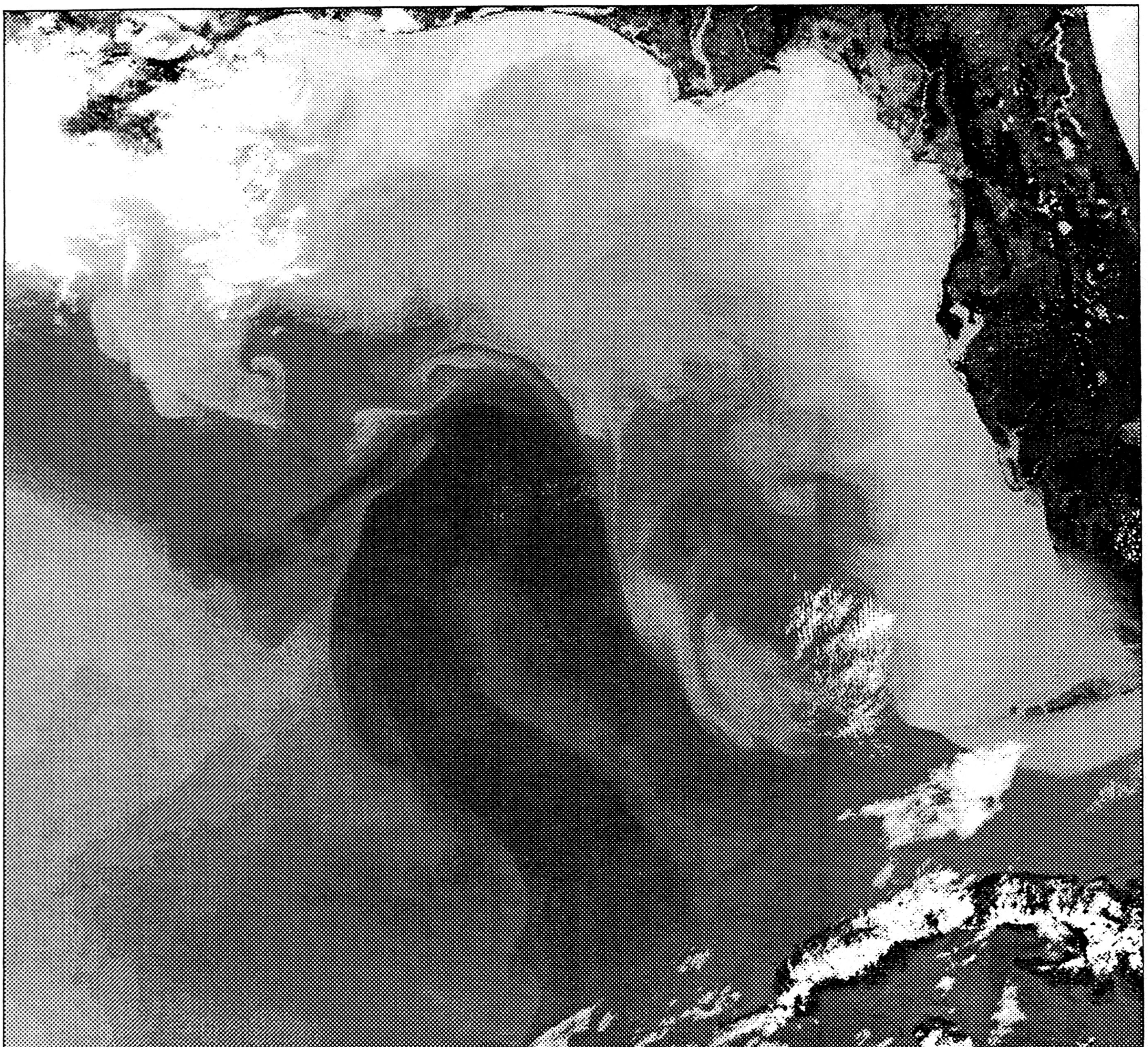


Fig. 1 AVHRR Infrared Imagery of the Northeastern Gulf of Mexico
The Loop Current, April 3, 1983

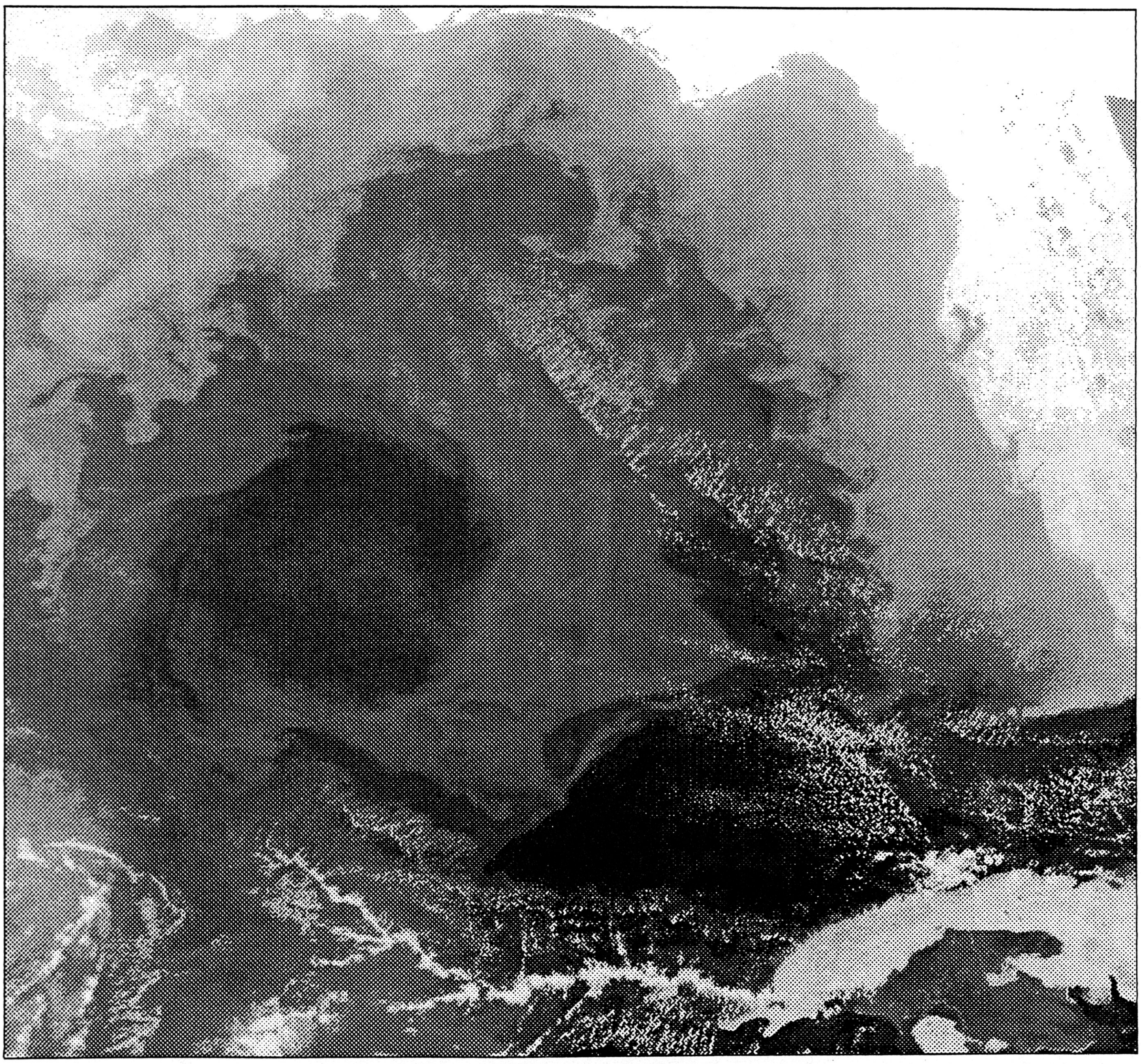


Fig. 2 AVHRR Infrared Imagery of the Northeastern Gulf of Mexico
An eddy pinching off from the Loop Current,
December 5, 1987.

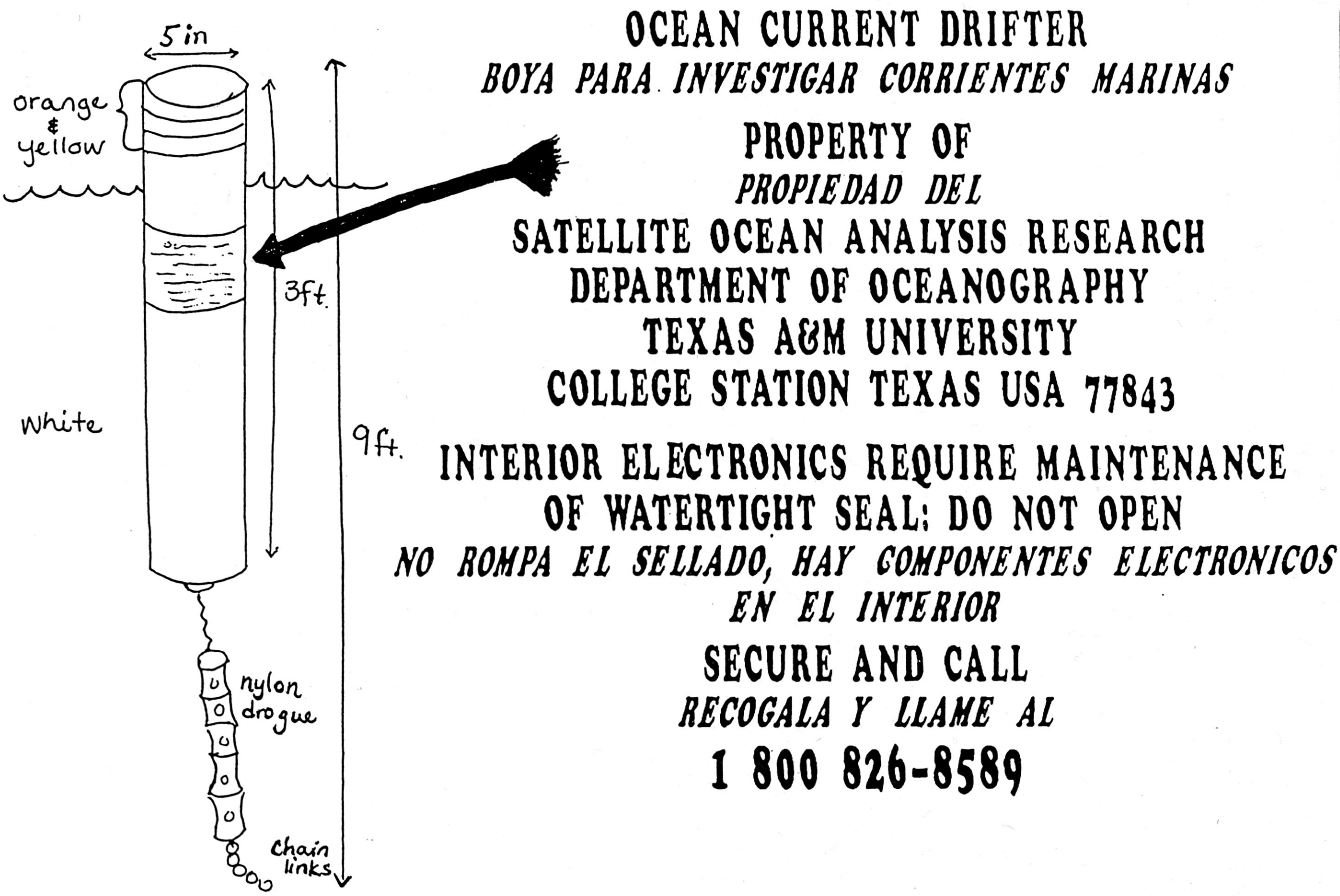


Fig. 3 Schematic of surface drifter and recovery label.

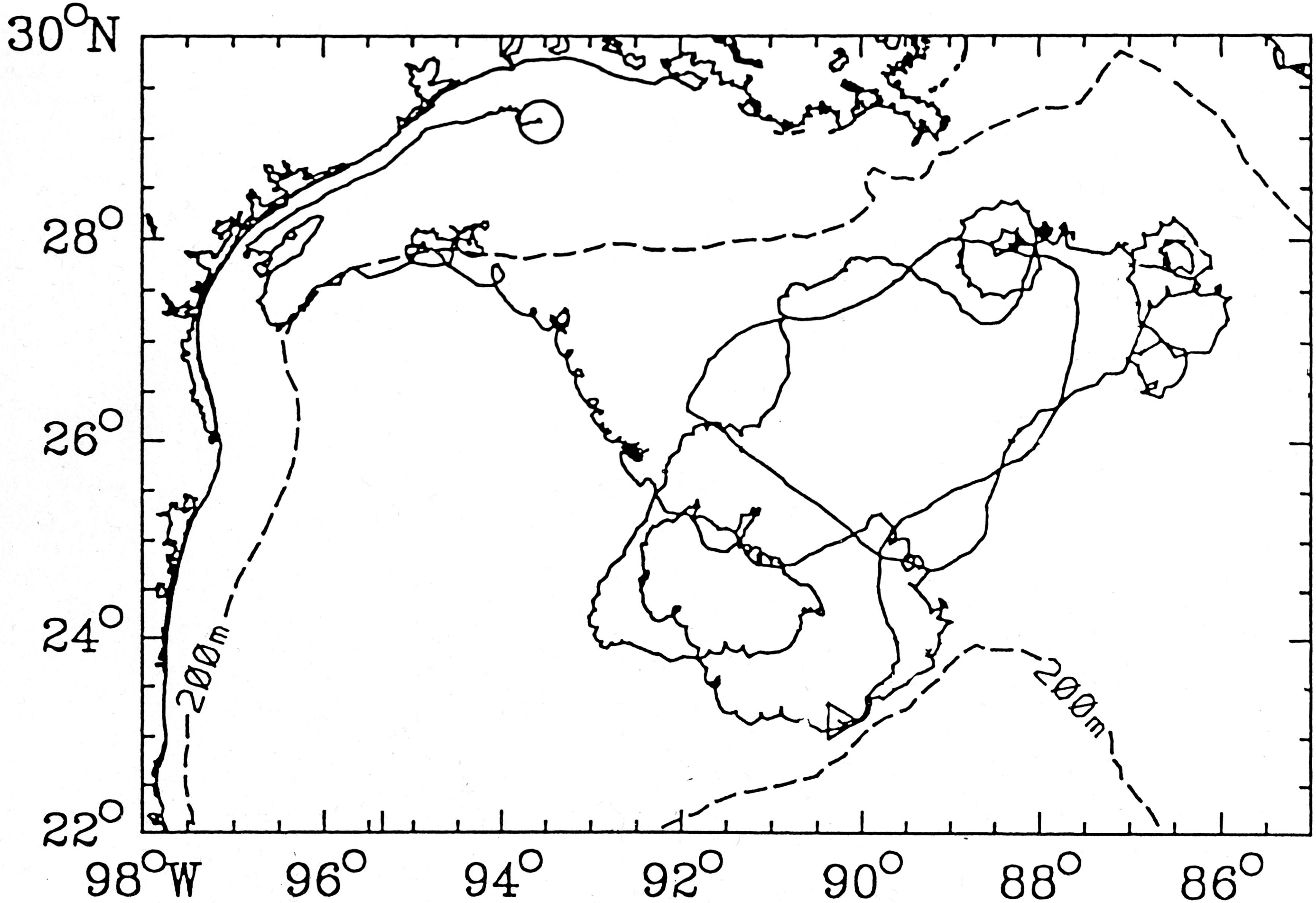


Fig. 4 Drifter 5545 trajectory, October 10, 1992 to November 2, 1993.

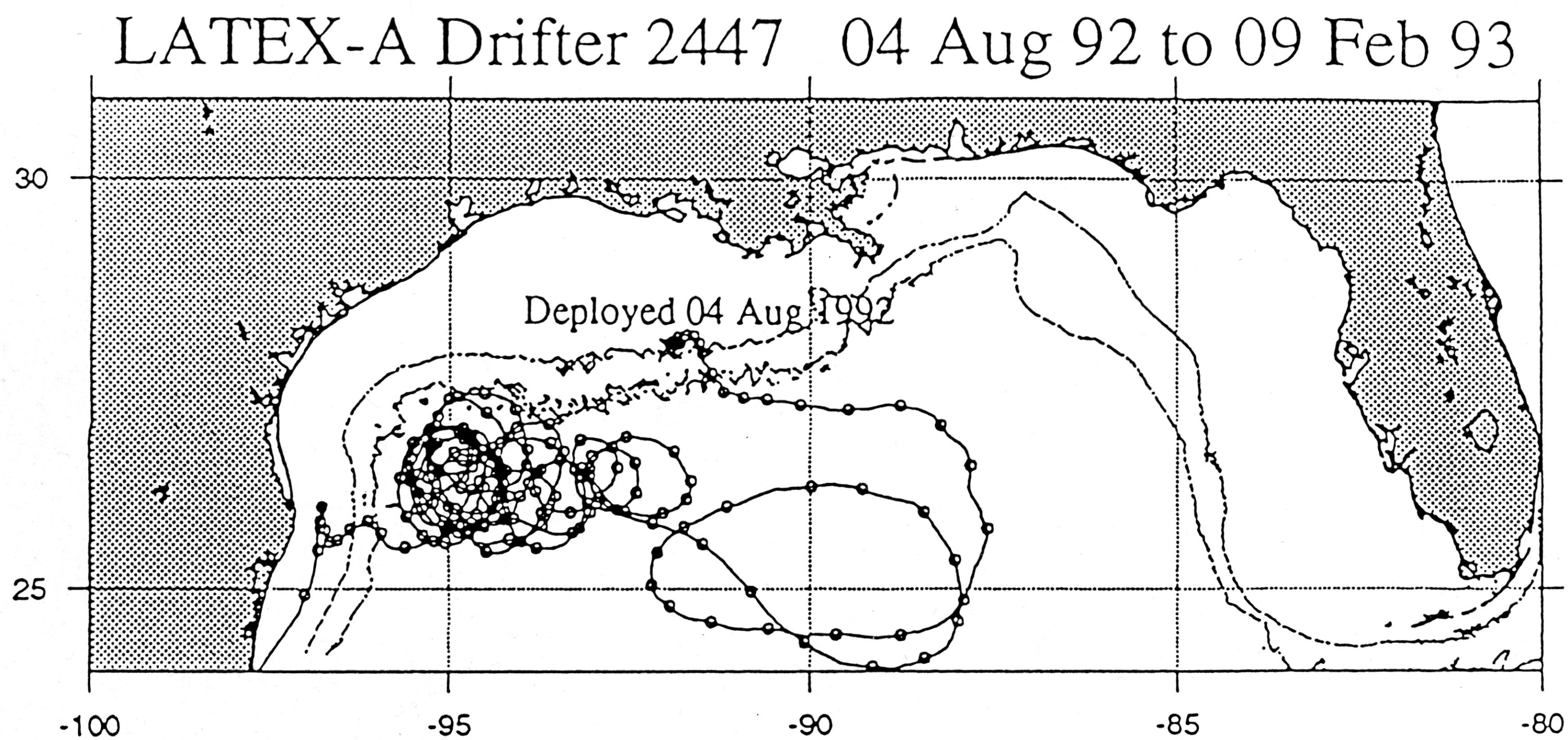


Fig. 5 Drifter 2447 trajectory, August 4, 1992 to February 9, 1993.

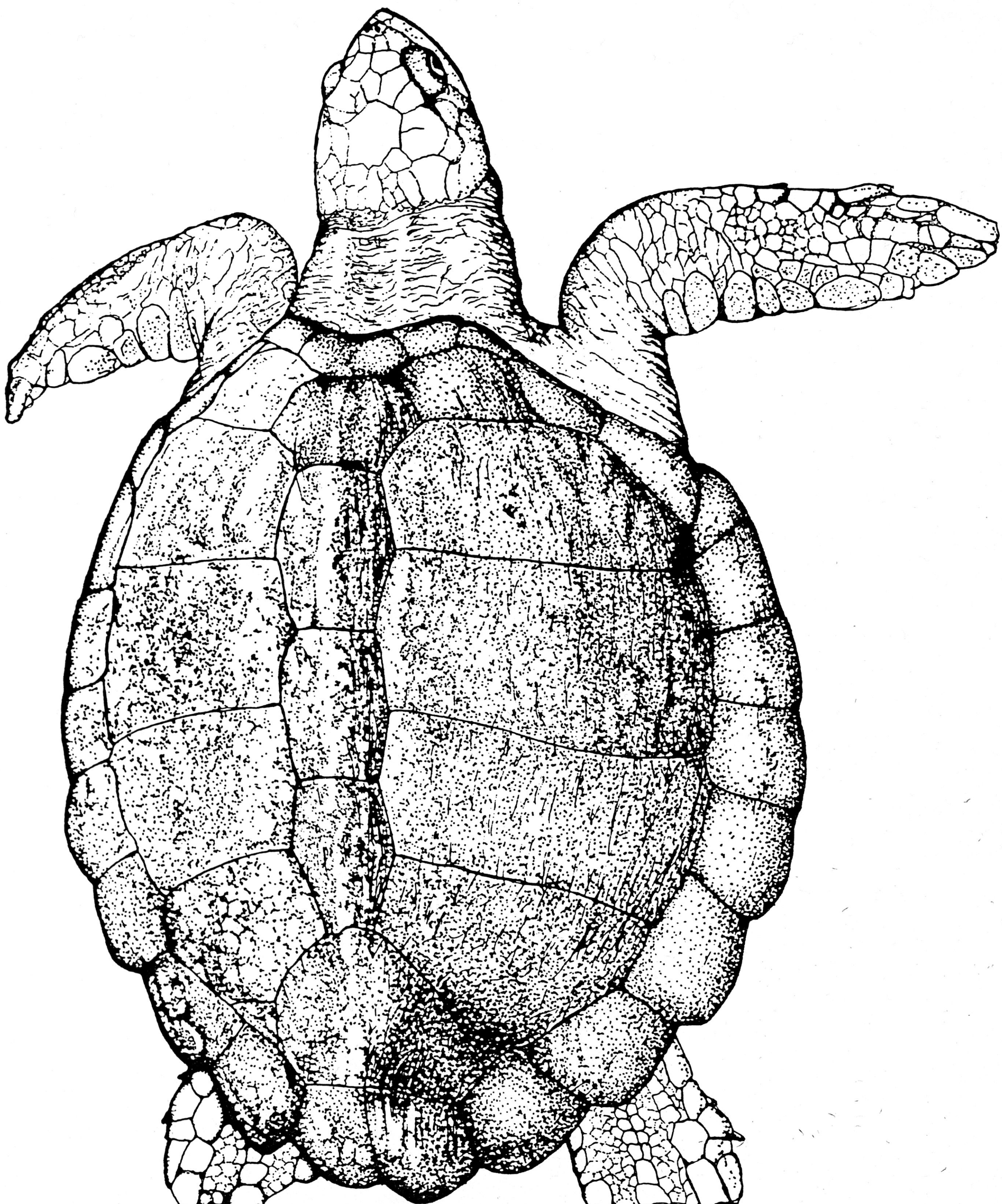


Fig. 6 Kemp's Ridley (*Lepidochelys kempi*) Sea Turtle.

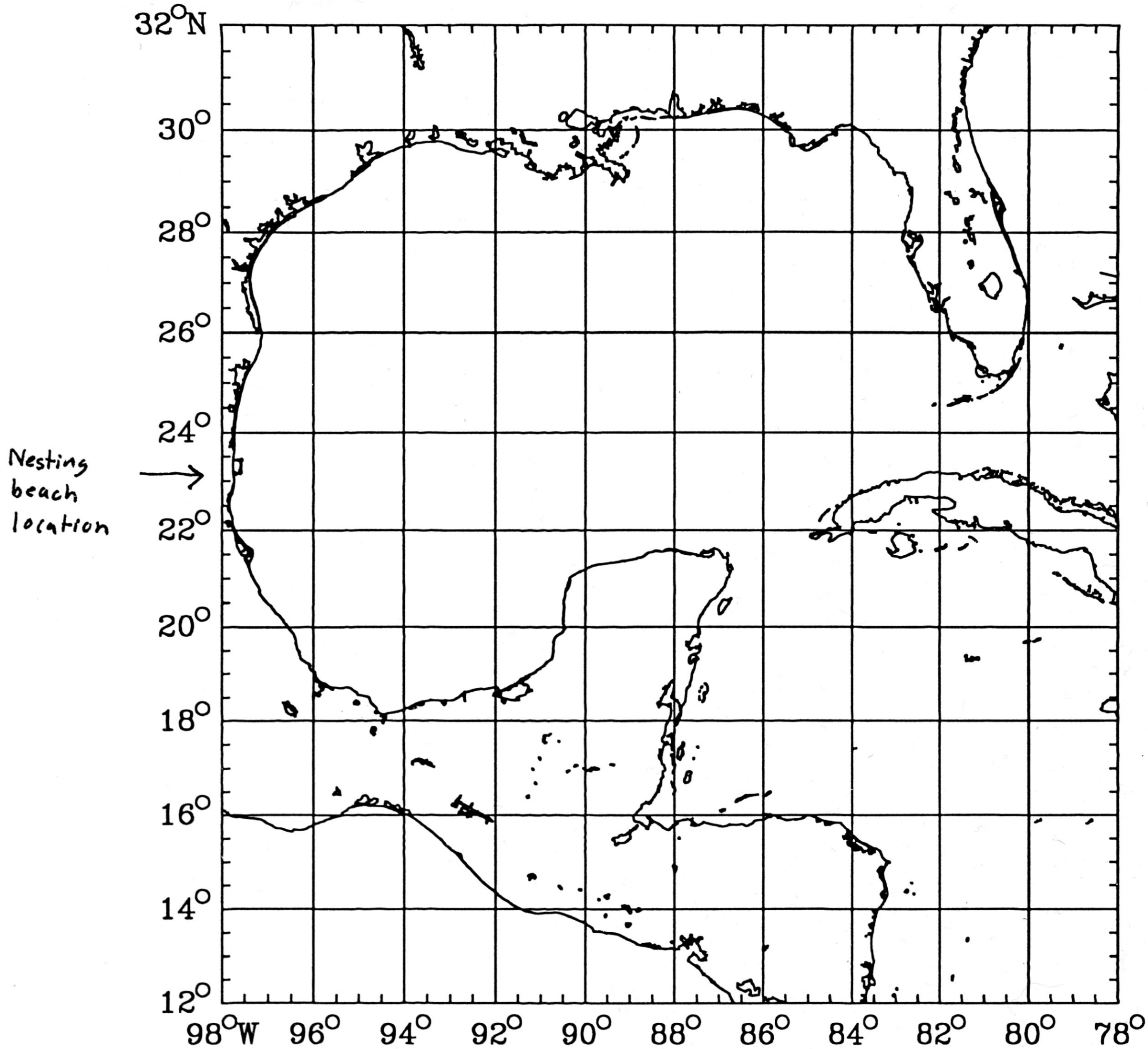


Fig. 7 Nesting beach location: 23°18'10" to 23°10'00" north, 97°45'40" to 97°45'30" west.

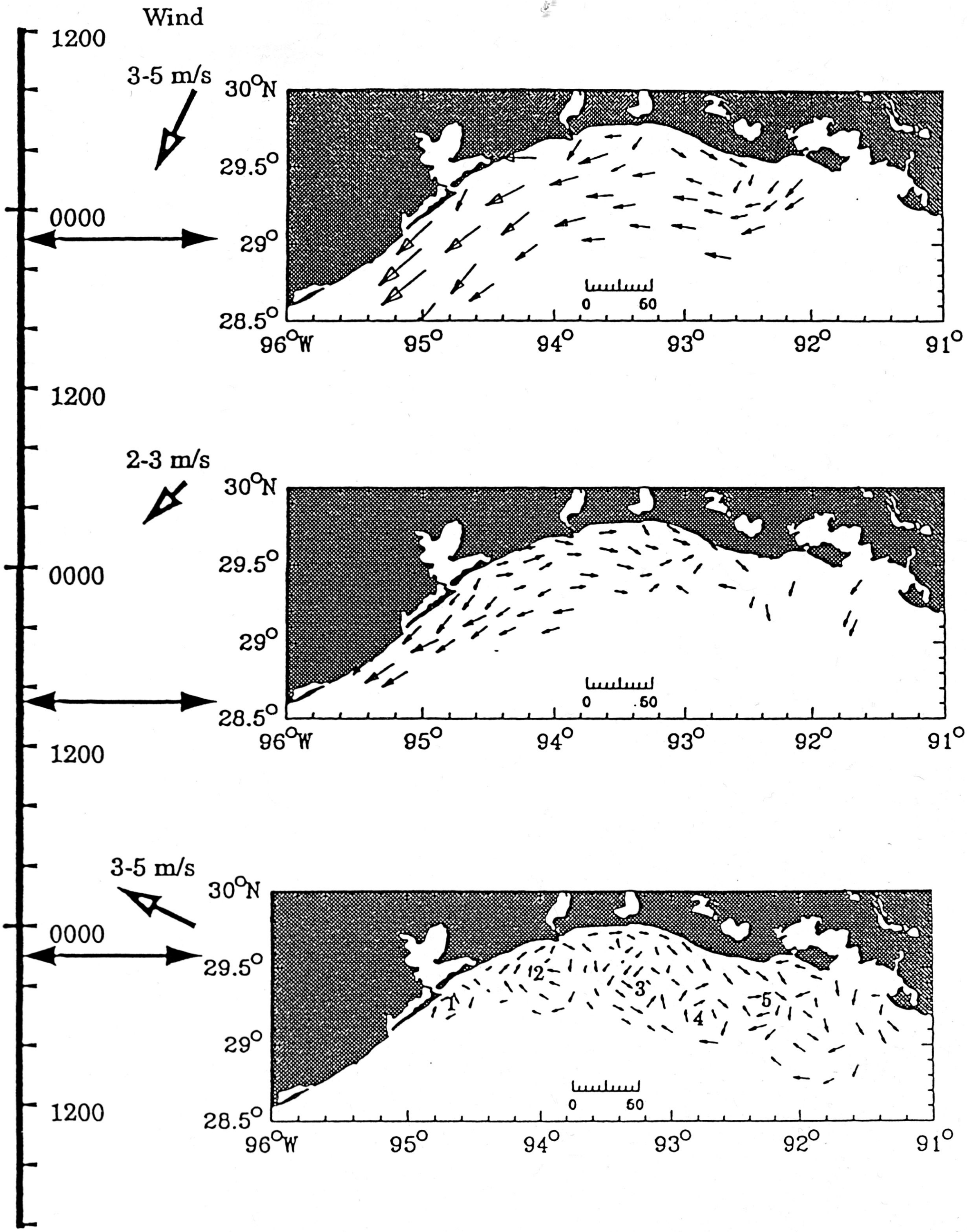


Fig. 8 Surface flow vector fields, October 4 to October 6, 1992 with coincident wind conditions (Vastano et al., in press).

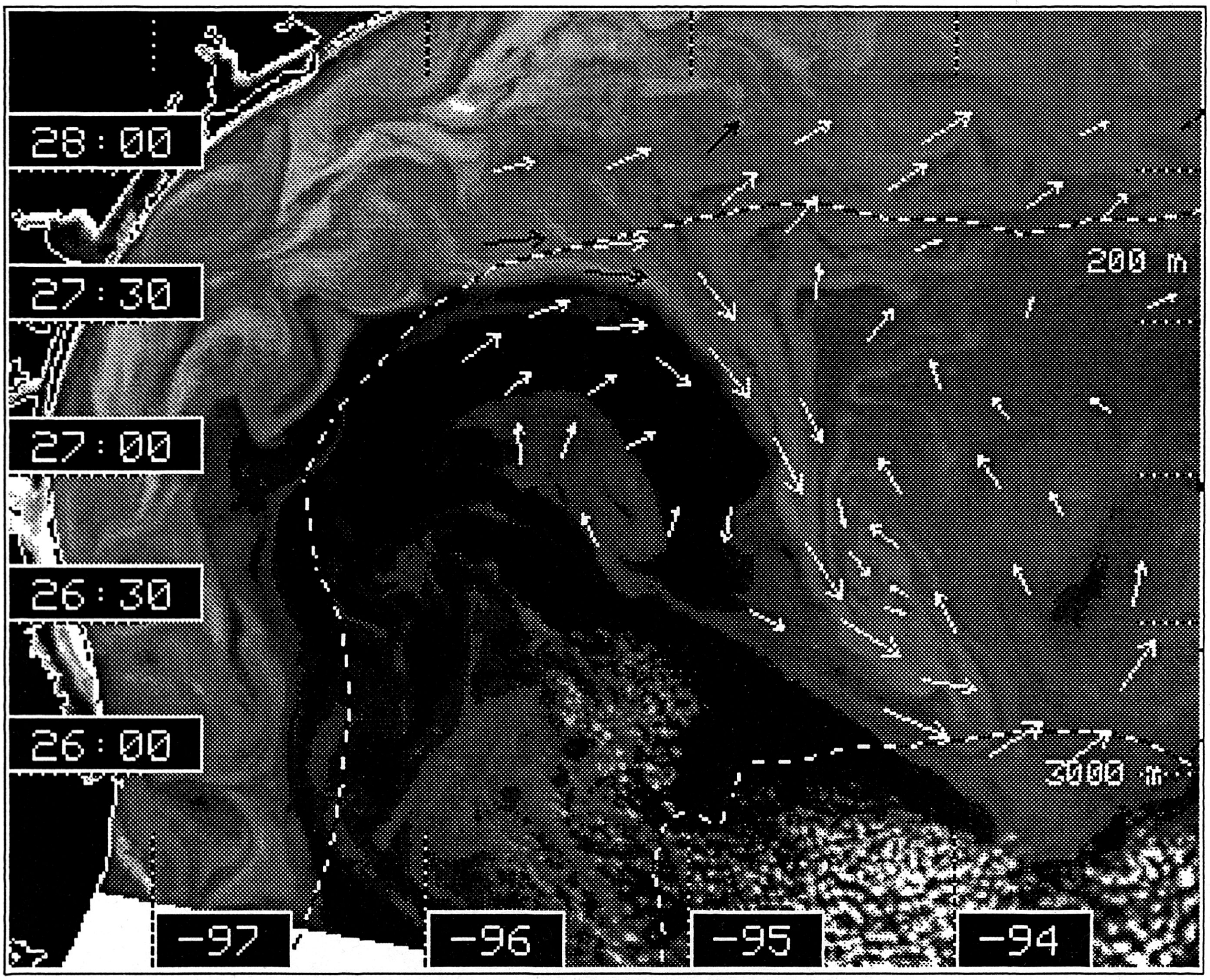


Fig. 9 AVHRR Infrared Imagery of the Northwestern Gulf of Mexico, April 22, 1989 with surface flow vector fields of the Texas Plume (Vastano, in press).

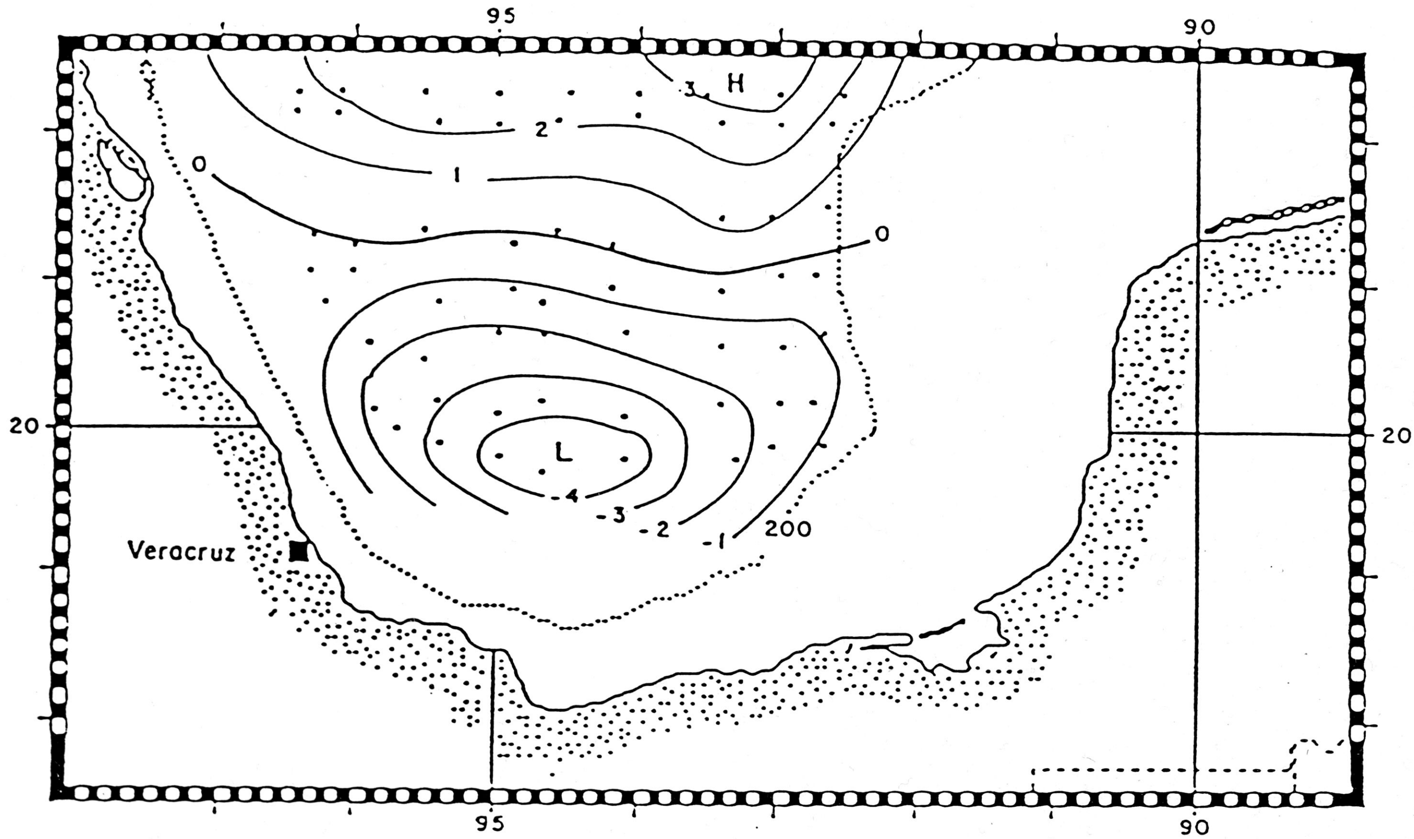
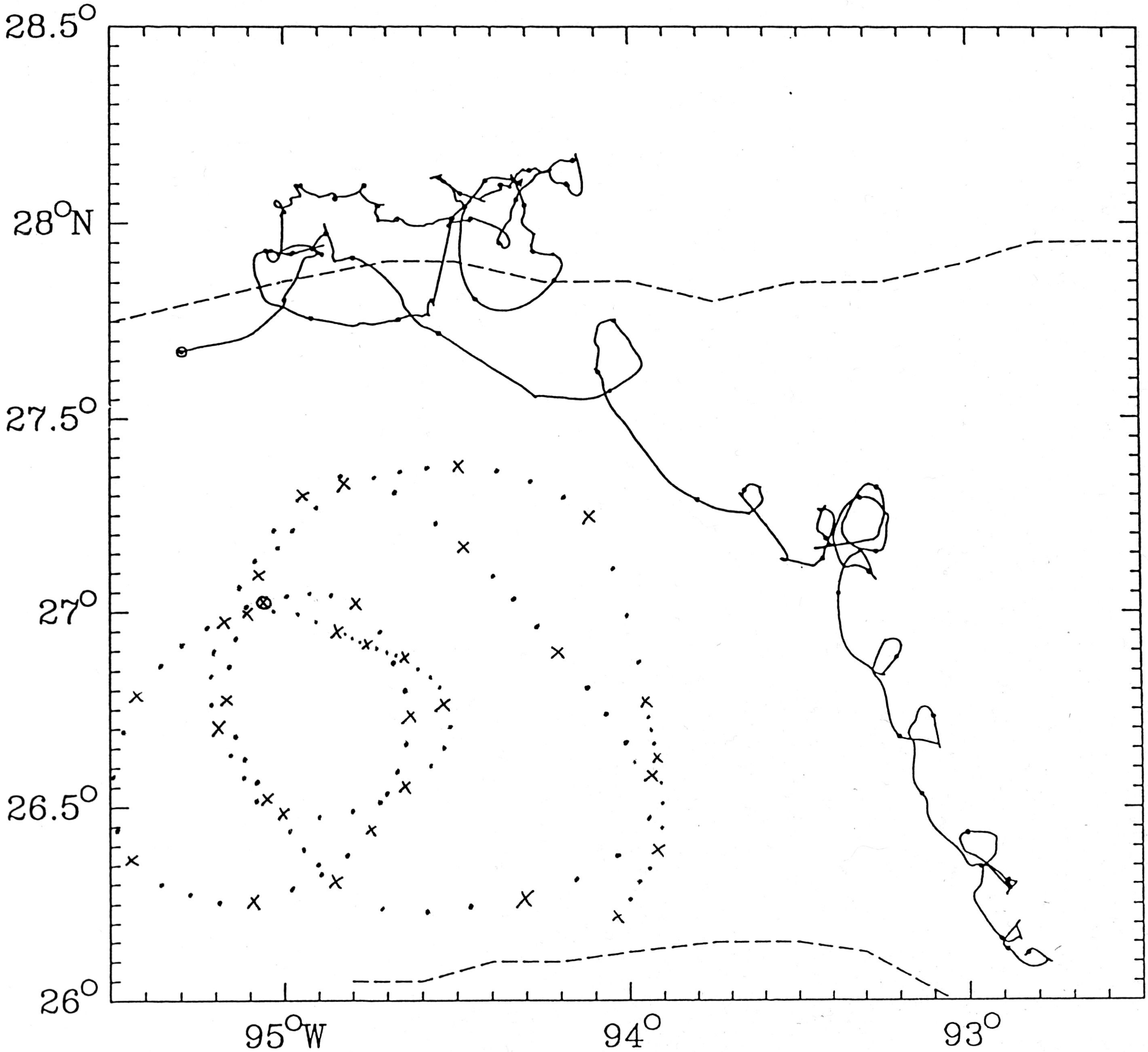


Fig. 10 Contours of the average field of the dynamic height of the sea surface relative to 425 db (Cerda, 1993).



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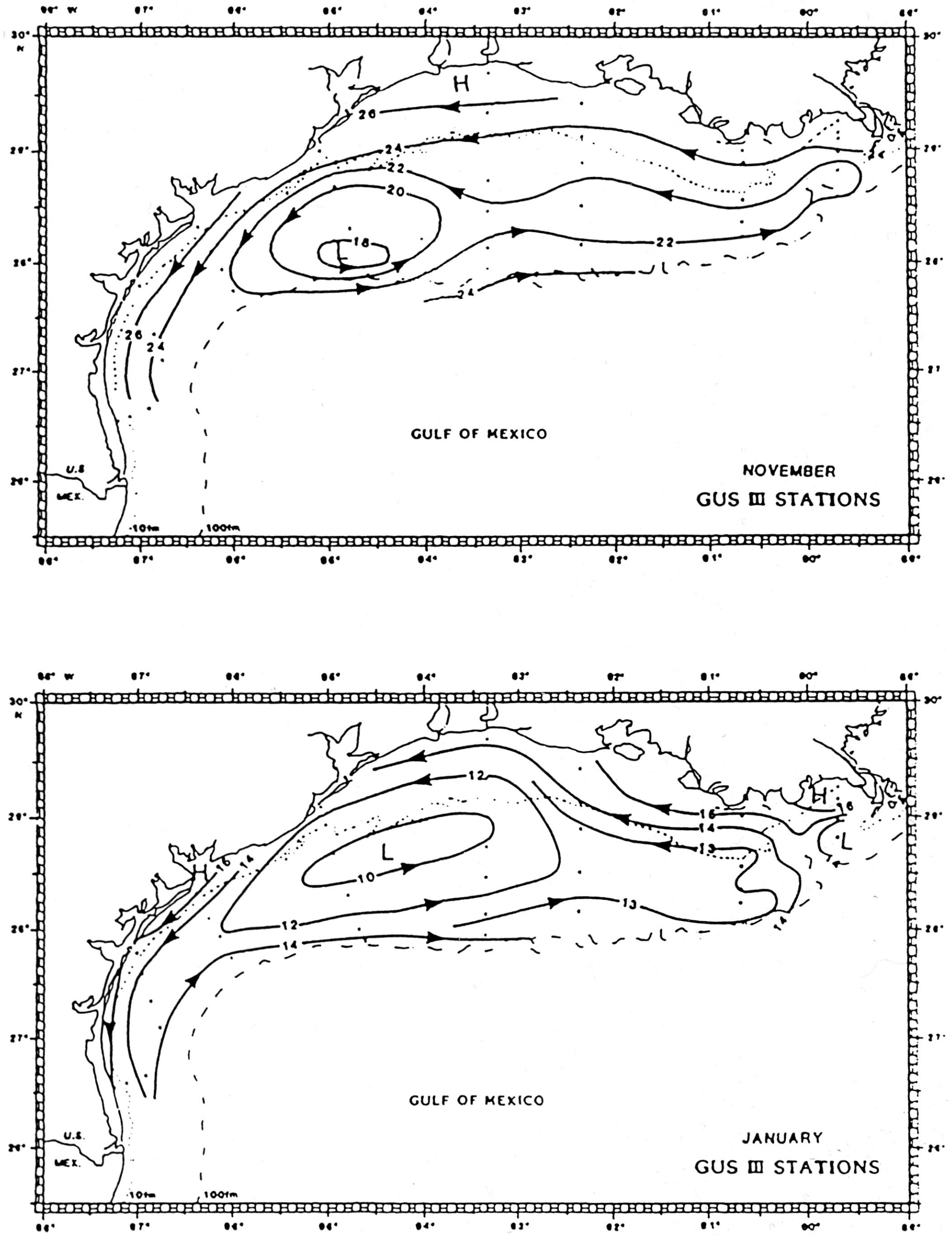

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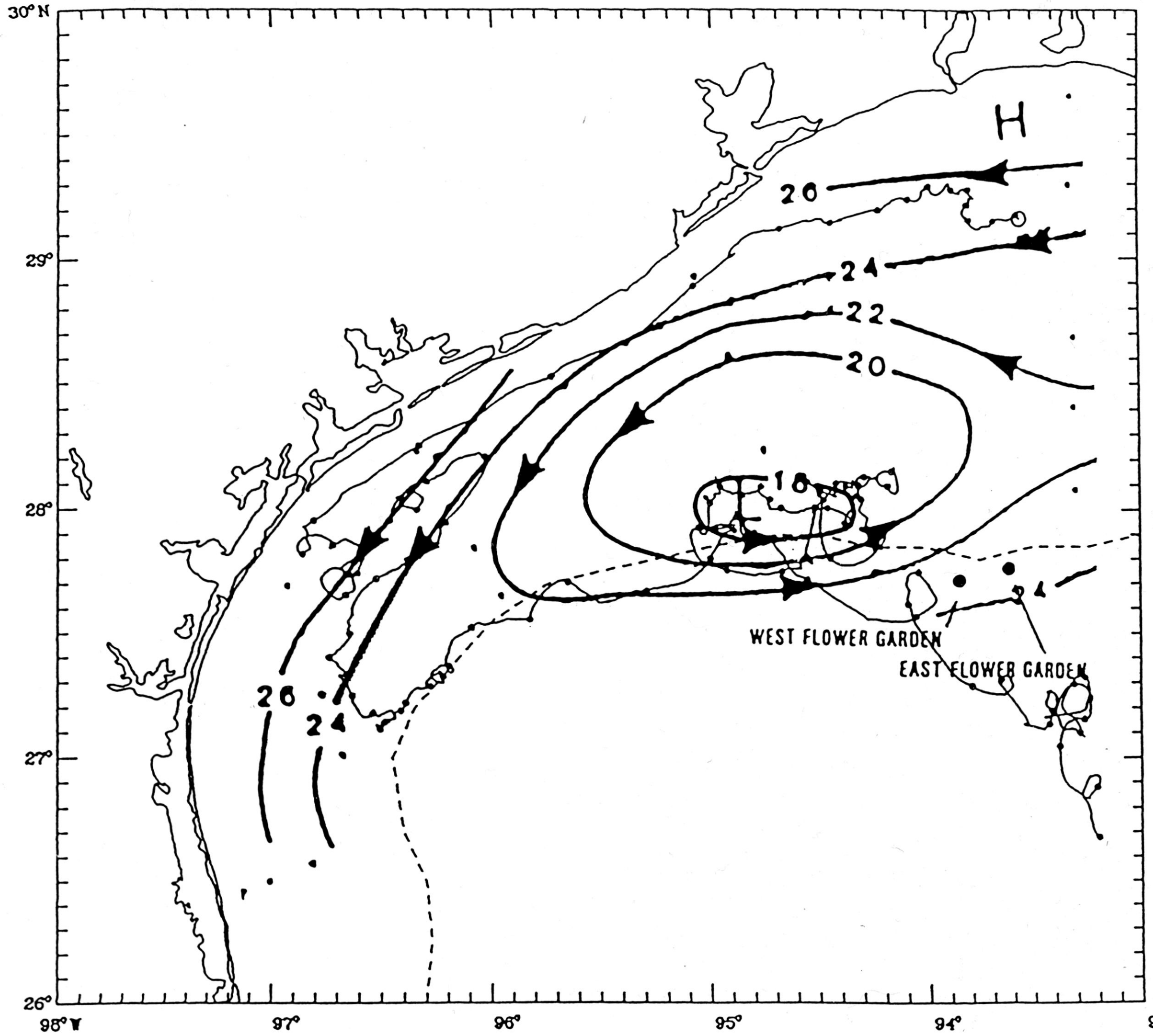

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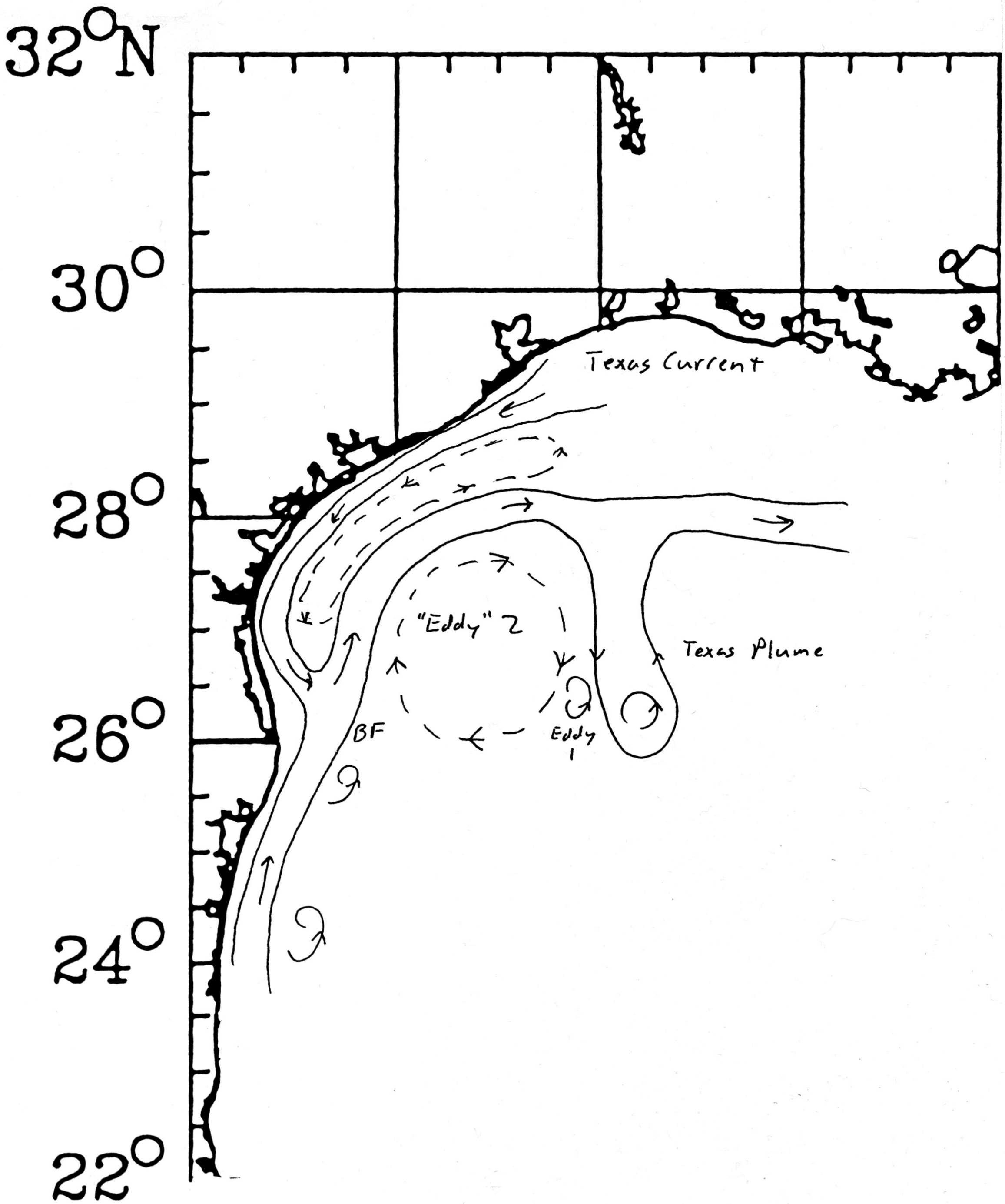

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