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The Invasion of the Red Tide In North Carolina Coastal Waters

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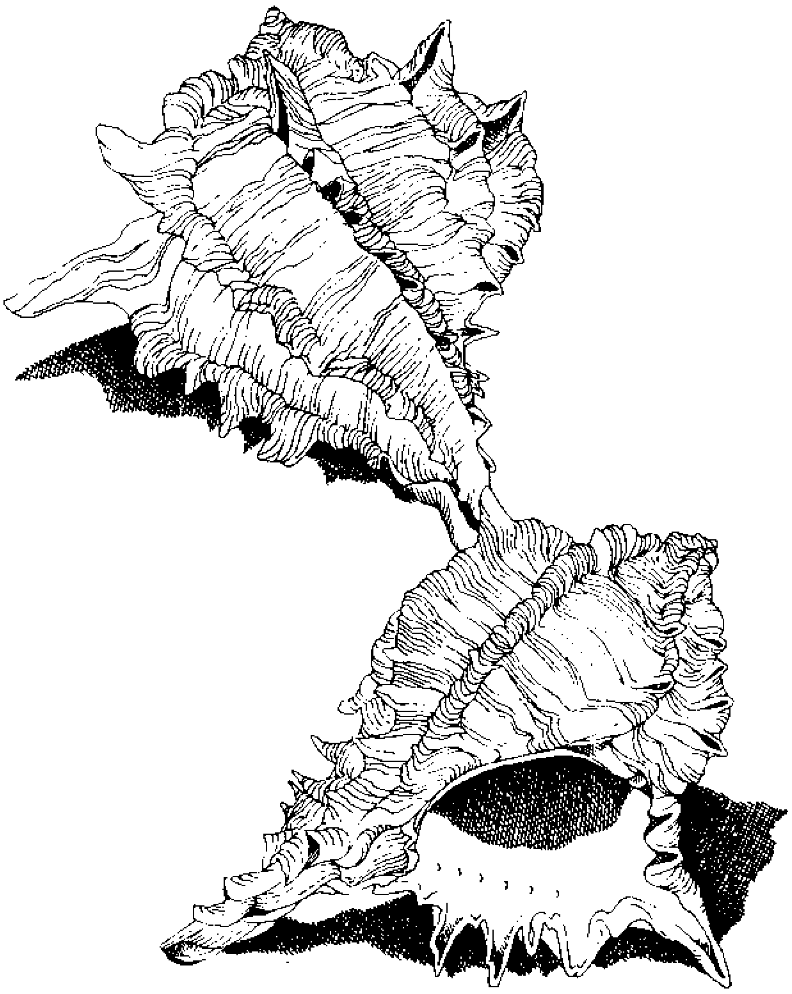

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I. INTRODUCTION

On or about Oct. 31, 1987, Onslow Bay (North Carolina) shelf waters became infested with a yellow-green organism identified as the dreaded "red tide". Investigators from the National Marine Fisheries Service (NMFS) determined that the yellow-green patches consisted of a one-celled plantlike organism named Ptychodiscus brevis, a red tide dinoflagellate.

The effects of the one-celled intruder were immediate and widespread. Shellfish such as clams, scallops and oysters became infected and were rendered inedible. This particular red tide organism contained a neurotoxin that affected the nervous systems of higher life forms, including humans. As the neurotoxins become airborne via breaking waves, beachcombers and surffishermen suddenly felt burning eyes and lungs and became nauseous and dizzy. Shellfishing was banned from Avon to Long Beach, and the beaches became deserted. The red tide, common to many coastal states including Texas, Louisiana, Florida, Connecticut and Massachusetts, was unknown in North Carolina waters. Moreover, the dinoflagelate was accompanied by a marine blue-green algae indigenous to subtropical waters (H. Paerl, p.c.). So, scientists immediately became suspicious that the dinoflagelate was transported to North Carolina from the south. If so, then what was the source and how was its pathway? We must consider the physical oceanography of the system to properly address these questions and to construct a possible scenario for this event.

II. PHYSICAL OCEANOGRAPHY OF THE CAROLINA CAPES SHELF

The hydrodynamics and hydrography of the Carolina Capes continental shelf, the region extending from Cape Romain, S.C. to Cape Hatteras, N.C. (cf. Figure 1), are controlled by atmospheric forcing from the top and by Gulf Stream frontal events from offshore. Gulf Stream phenomena that affect the oceanography of the Carolina Capes shelf include the deflection of the stream at the Charleston Bump (Pietrafesa et al, 1978; Brooks and Bane, 1978) and the subsequent creation of the Charleston Trough (Pietrafesa, 1983) and frontal meanders and filaments (cf. Figure 2). Atmospheric wind effects are most apparent in mid to inner shelf waters. In offshore waters, wind effects are superimposed on frontal events.

Wind effects are both mechanically direct in the surface layer and indirect via the setup of sea-level gradients throughout the water column. The shelf current field that relates to wind forcing consists of a wind-driven surface layer component and slope currents which extend throughout the water column. According to classical Ekman theory (Ekman, 1905), the transport in the wind-driven surface layer is 90° to the right of the wind.

Gulf Stream frontal events are manifested as either meanders or filaments. Actually filaments are meanders that have folded backwards at the crest of the meander to form a tongue like extension of the Gulf Stream onto the shelf. Both features are actually wave-like instabilities of the Gulf Stream front as has been discussed by Pietrafesa and Janowitz (1980). The Pietrafesa-Janowitz results are consistent with satellite sea surface temperature observations (Legeckis, 1979). They suggest that an individual meander is a long wave with length the order of 100 to 300 km centered about the Gulf Stream front and moving with the Gulf Stream so that the manifestation of sense of propagation is to the north(east). Within the wave crest, which is in the Gulf Stream proper, the

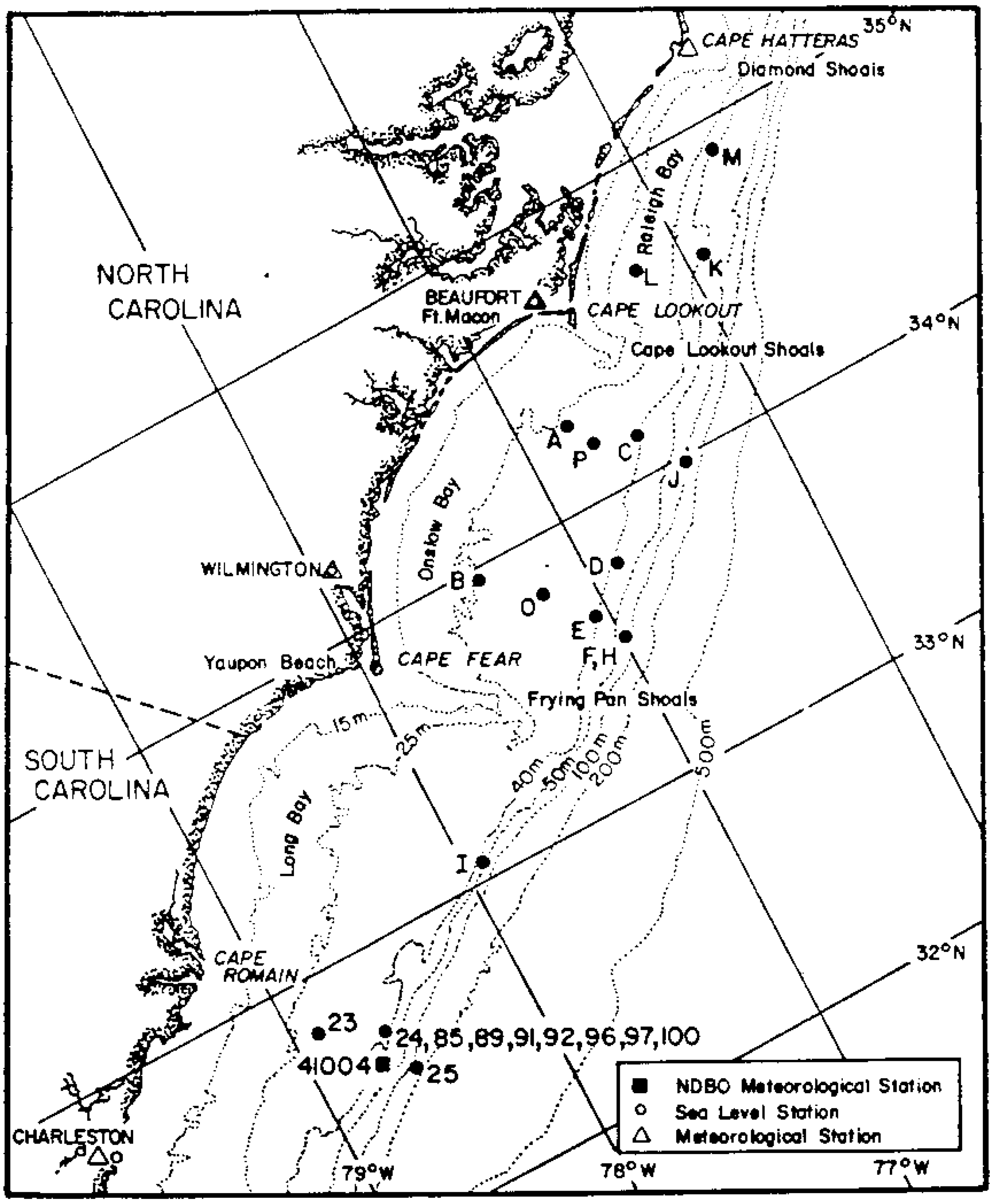


Figure 1. Topographic setting and configuration of the Carolina Capes continental margin. Lettered and numbered dots denote NCSU current meter mooring stations maintained variously between 1975 - 1979.

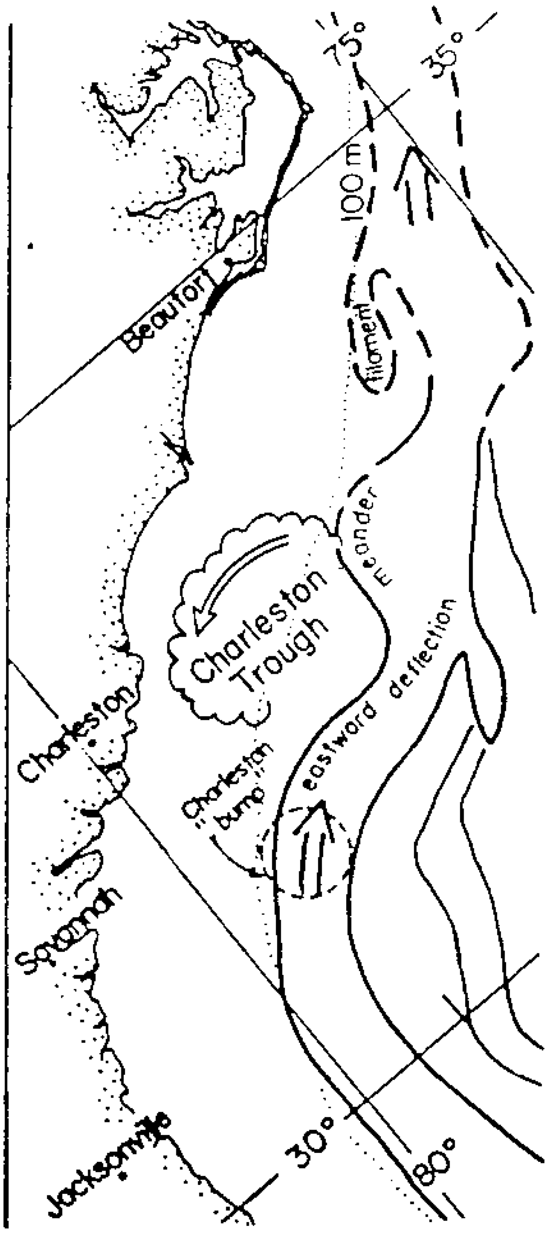


Figure 2. General configuration of Gulf Stream in the South Atlantic Bight. Note, Gulf Stream generally hugs the 100-meter isobath south of Savannah, is deflected eastward at the Charleston bump, subsequently forms a counterclockwise rotating low pressure center, called the Charleston Gyre or Trough, and forms frontal meanders and filaments.

streamlines of flow in the water column follow the shape of the crest and thus have a net anticyclonic sense of turning. In the wave trough, there is a closed, cyclonically rotating cell, a "cool pool." Filaments can be best described as meanders that grow in crest amplitude in the horizontal plane, such that the crests become unstable and fold back around the cool pool sitting in the wave trough. As the wave crest folds back toward the coast, shallower depths are encountered and the vertical vorticity constraint requires that the anticyclonic motion along the streamline of the wave crest be augmented. Flow is to the north on the shoreward side of the event and to the south on the offshore side of the filament (Figure 3).

The warm Gulf Stream waters, which define the filament, deepen due to the downward vertical velocity produced by the increased negative relative vorticity to the east (i.e. offshore, of the filament). To the west (i.e. onshore) of the Gulf Stream front is a cold water mass that is cyclonically rotating and is, in fact, the trough of the mother wave. The filament formation occurs in concert, either as cause or effect, just as the wave trough realizes an intensified cyclonic torque and spins up more intensely. The net effect is a rapid vertical ascension of isopycnals, a "doming up" phenomenon (Figure 4). As the filament advects north(east)ward along the Gulf Stream front, a series of shelf-break/slope cool pool eddies are spun up. As a consequence, nutrients are advected upwards also (Figure 5) to form an upwelled ridge of nutrients and cold water, which as a function of the intensity of cyclonic torqueing, has a peak that varies in elevation. Underneath the warm, clockwise rotating filament is a bottom boundary layer in which cold, upwelled, nutrient rich waters are advected shoreward. This entire scenario is presented in Figure 6. We now return to the red tide event.

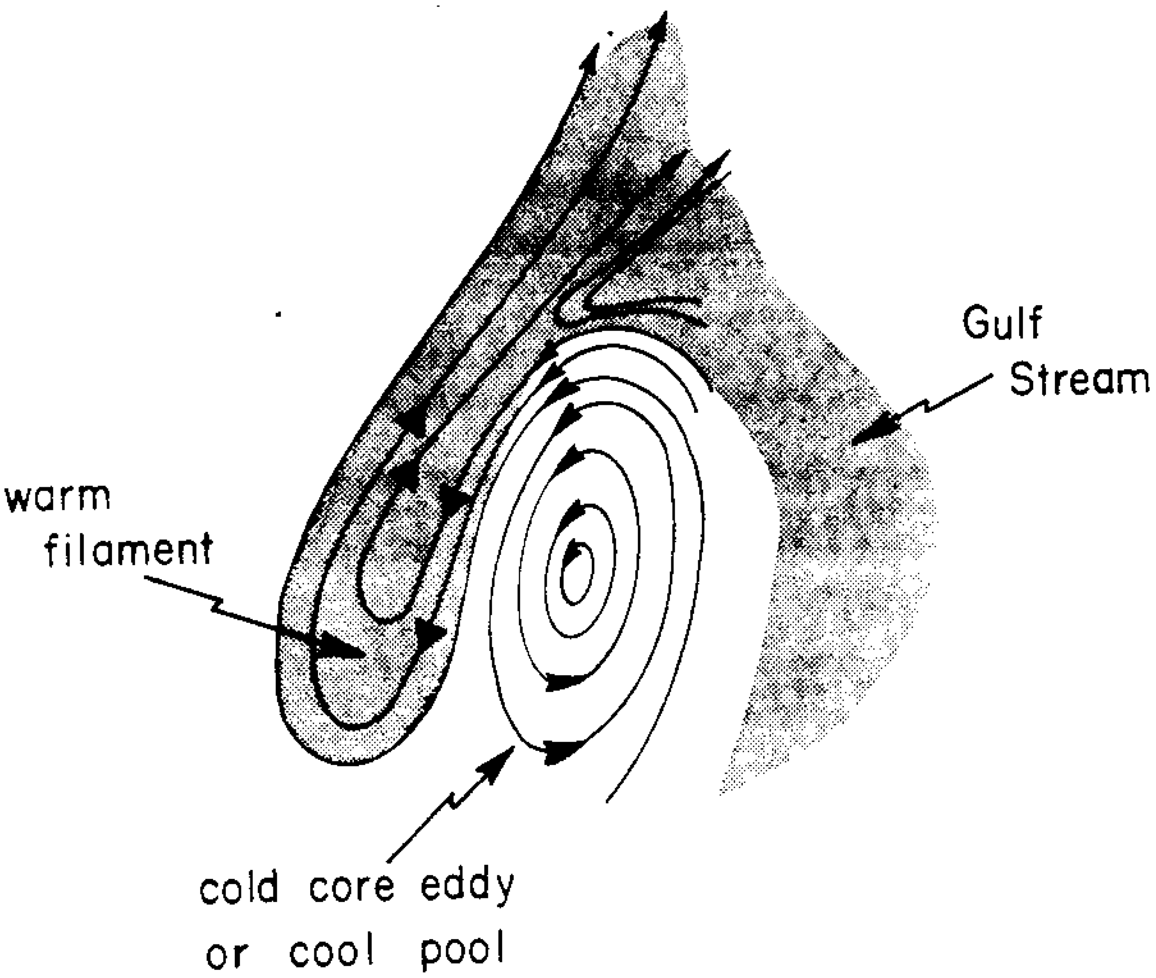


Figure 3. Surface, horizontal plane flow field in a Gulf Stream frontal filament and its cold core eddy (the cool pool). Arrows indicate direction of currents. Shaded area indicates warm water, and non-shaded area indicates cool water.

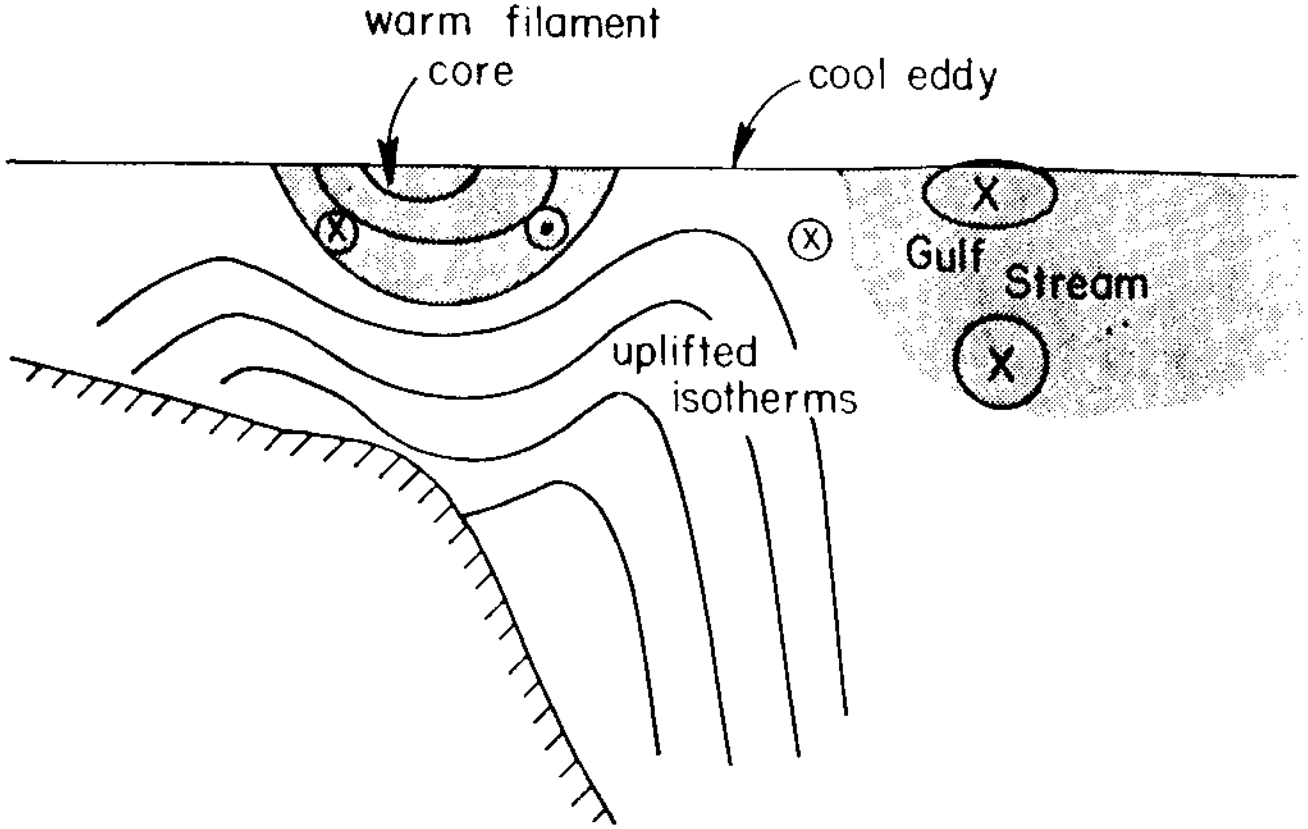


Figure 4. Cross-sectional temperature and longshore velocity structure across a Gulf Stream frontal filament and its cold core eddy.

▨	Warm water	
〰	Lines of constant temperature	
⊗	Flow into paper	note: magnitude of flow is suggested by size of ellipse
⊙	Flow out of paper	

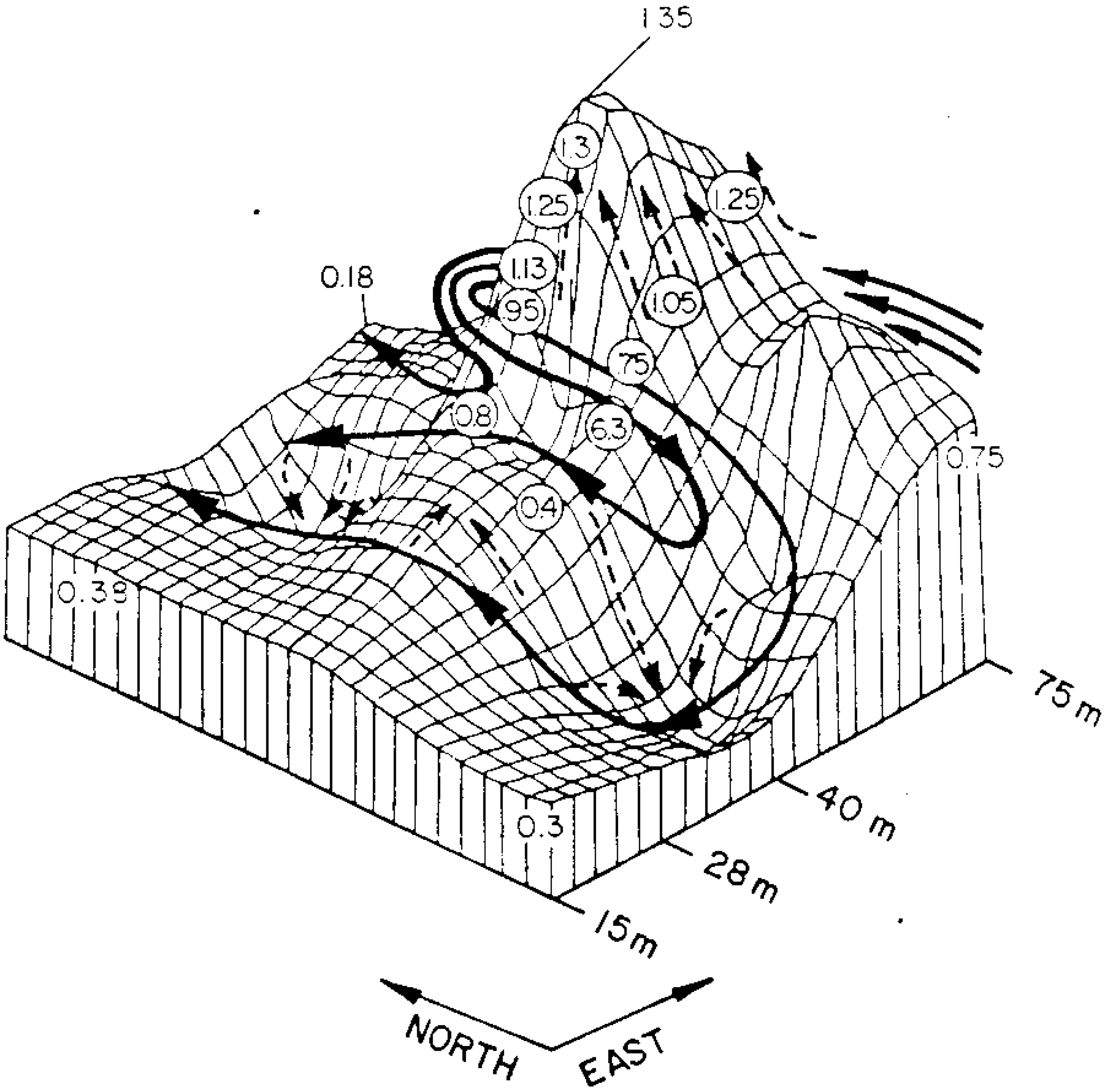


Figure 5. Across and alongshelf contour map of concentration of phosphate at a constant height of 3 meters above the bottom during the passage of a Gulf Stream frontal filament on the North Carolina shelf. Relative values of PO_4 (in microgram atoms per liter) are high in the "cool pool" and low in the warm filament. Arrows indicate direction of currents.

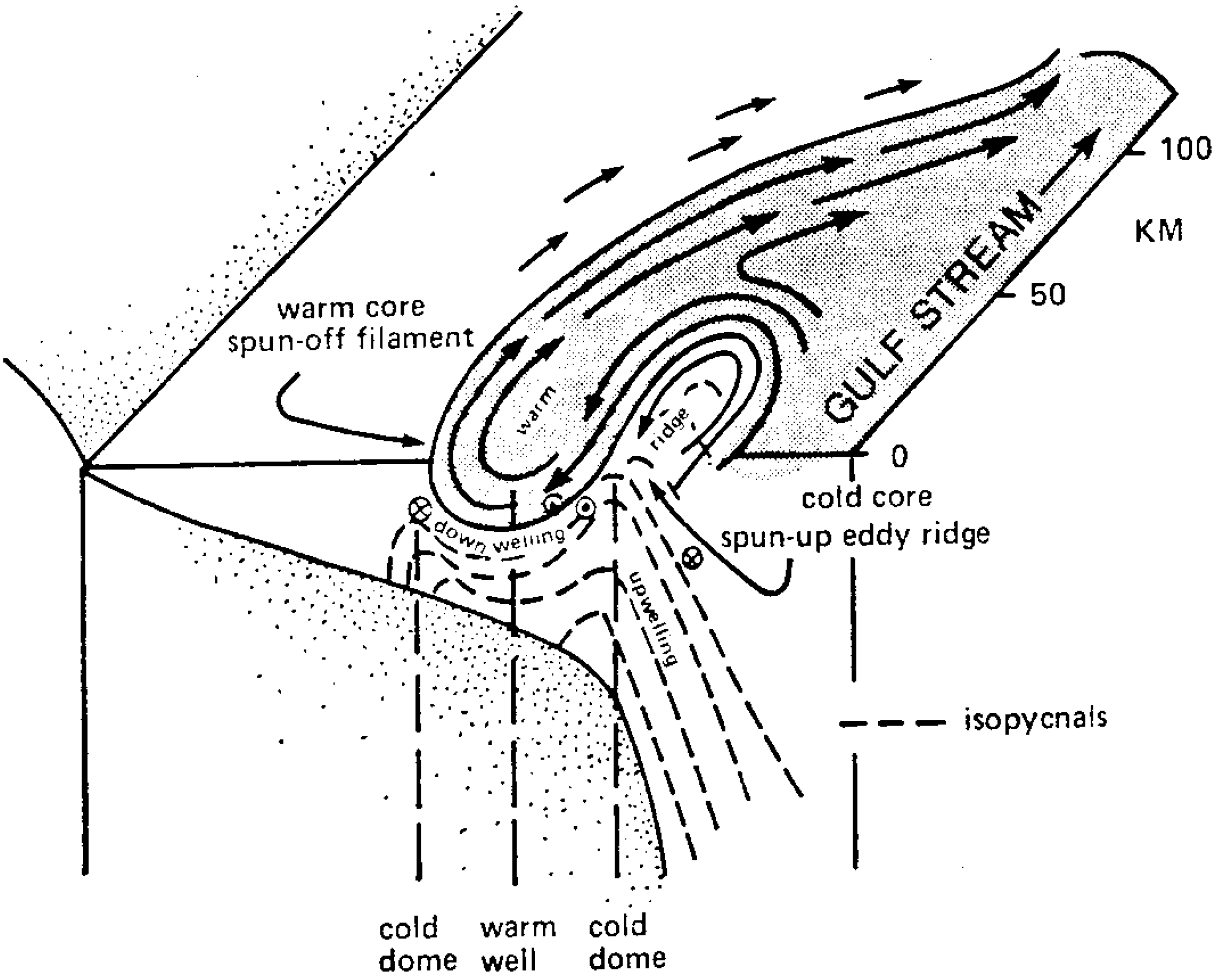


Figure 6. 3-D view of a moving Gulf Stream clockwise rotating frontal filament, its associated counter-clockwise rotating cool pool or cold core eddy (ies) and the upwelled ridge caused by the superposition of cool pools.

III. INVASION OF THE RED TIDE

On Aug. 24, 1987, a breakout of the red tide was reported off the coast of Naples, Florida, in the Gulf of Mexico. Naples is approximately 1,600 kilometers (1,010 miles), as the Loop and Gulf Stream Currents flow, from Onslow Bay. If the red tide organism were able to jump aboard the Loop Current in the Gulf of Mexico, it could have been transported down the west Florida coast, past the Florida Keys and through the Florida Straits where it would have become part of the northward flowing Gulf Stream. From the east coast of Florida, the organism would have traveled north reaching Onslow Bay outer shelf waters sometime in early October. This travel would have taken 37 to 52 days given the typical water-parcel speeds of 35 to 50 cm/sec that exist in the coastward side of the Gulf Stream frontal region (Pietrafesa, 1988). That would have placed the dinoflagellates some 80 to 120 kilometers (50 to 75 miles) off the Carolina coast between Oct. 5 to 11. Could frontal filament dynamics and the windfield have subsequently driven dinoflagellate-laden currents to the coast? Let us first consider the conditions that were present at the time.

In Figure 7a, the National Weather Service atmospheric pressure map for Aug. 24, 1987 shows a high pressure center located in the southeastern US. The winds associated with this weather system on the west Florida shelf were to the south thereby effecting an offshore transport of surface waters from the shelf into the Loop Current. Two weeks later we find a low pressure center or atmospheric cyclone located in the southeast, as shown in the Sept. 7 weather map in Figure 7b. The winds are to the north on the east Florida shelf thereby drivng surface coastal waters offshore into the Gulf Stream, so while the red tide organisms were in the area of the east Florida shelf, winds were unfavorable for

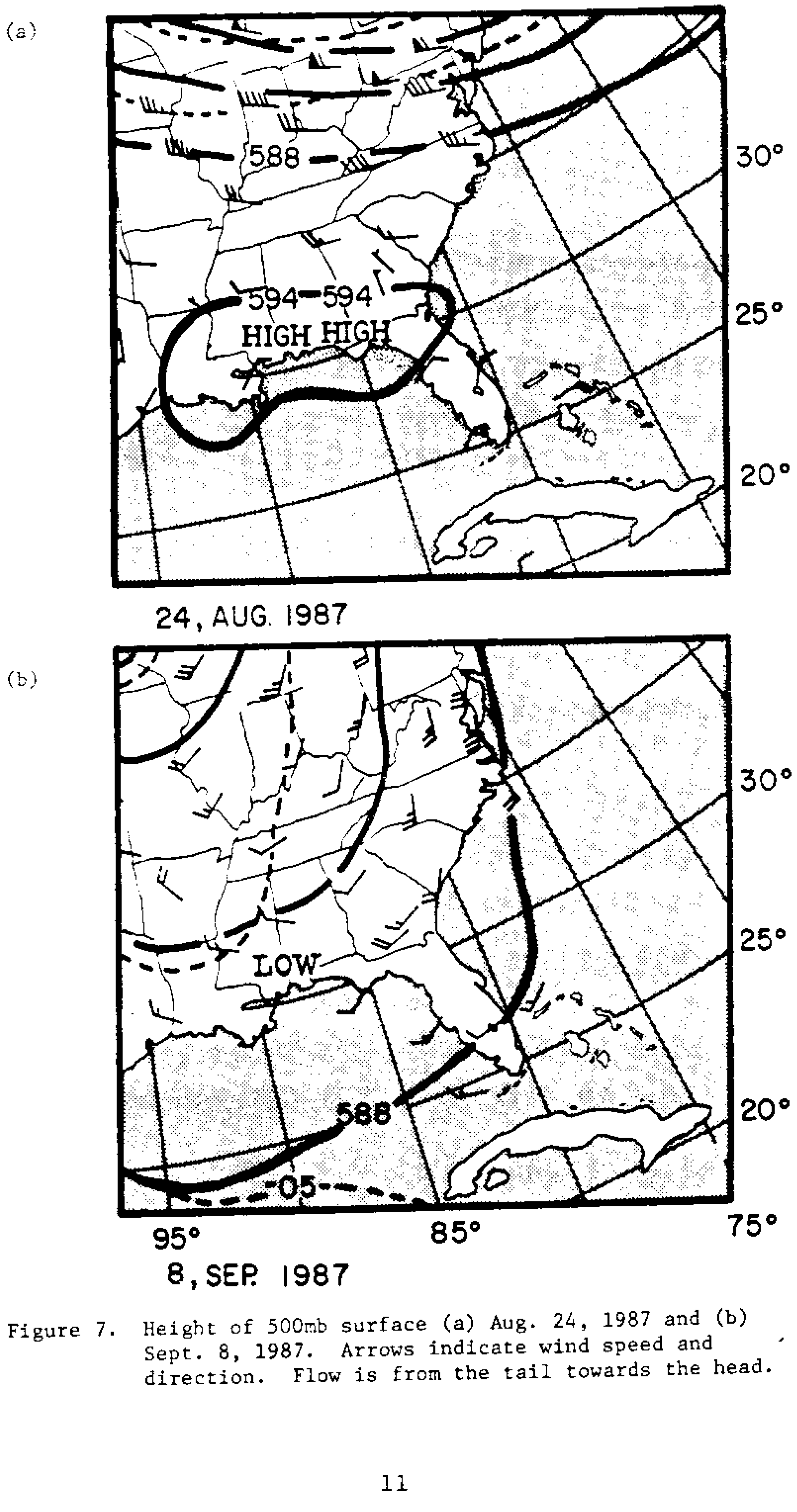


Figure 7. Height of 500mb surface (a) Aug. 24, 1987 and (b) Sept. 8, 1987. Arrows indicate wind speed and direction. Flow is from the tail towards the head.

onshore transport. So the organisms stayed in the Gulf Stream and were transported for the next two weeks towards North Carolina.

Sea surface temperature imagery collected via the NOAA-9 Advanced Very High Resolution Radiometer (AVHRR) sensor on Oct. 05, indicated two frontal filaments located between 32° and 33.5° latitude (cf. Figure 8a). By Oct. 09 the northernmost of the two filaments was relocated northeast of Cape Hatteras. The southern filament moved to Onslow Bay offshore waters (cf. Figure 8b). Two additional filaments had, by then, formed due east of Beaufort, S.C., and Cape Romain, S.C.

For the filament located offshore of Onslow Bay to have propagated there from its previous location offshore of Charleston, S.C., it would have had a phase speed of approximately 42 cm/sec or 36 km/day. If this phase speed of propagation is representative of the speed of parcel movement along the western wall of the Gulf Stream, the Gulf Stream frontal zone, then it would have taken a patch of water and its constituents 45 days to go from Naples, Fla. to Onslow Bay. This agrees with our earlier estimates. So red tide dinoflagellates loaded into the Loop Current in the Gulf of Mexico offshore of Naples, Fla., could have been positioned in a large Gulf Stream frontal filament offshore of Onslow Bay on Oct. 09. If the dinoflagellates were located in surface layer waters of the filament then the obvious question occurs: How could the dinoflagellates have been transported out of the filament and across Onslow Bay, a distance of 90 to 110 km (56 - 68 mi.) by Oct. 31 when the red tide was first observed on the beaches? To address this question we must ask an additional one. What physical processes could exist at this time of year that would move one-celled, microscopic drifters across the width of Onslow Bay? There are two likely candidates: the tide and the wind. We first consider the tide.

Pietrafesa, et al (1985) provide a comprehensive overview of tidal

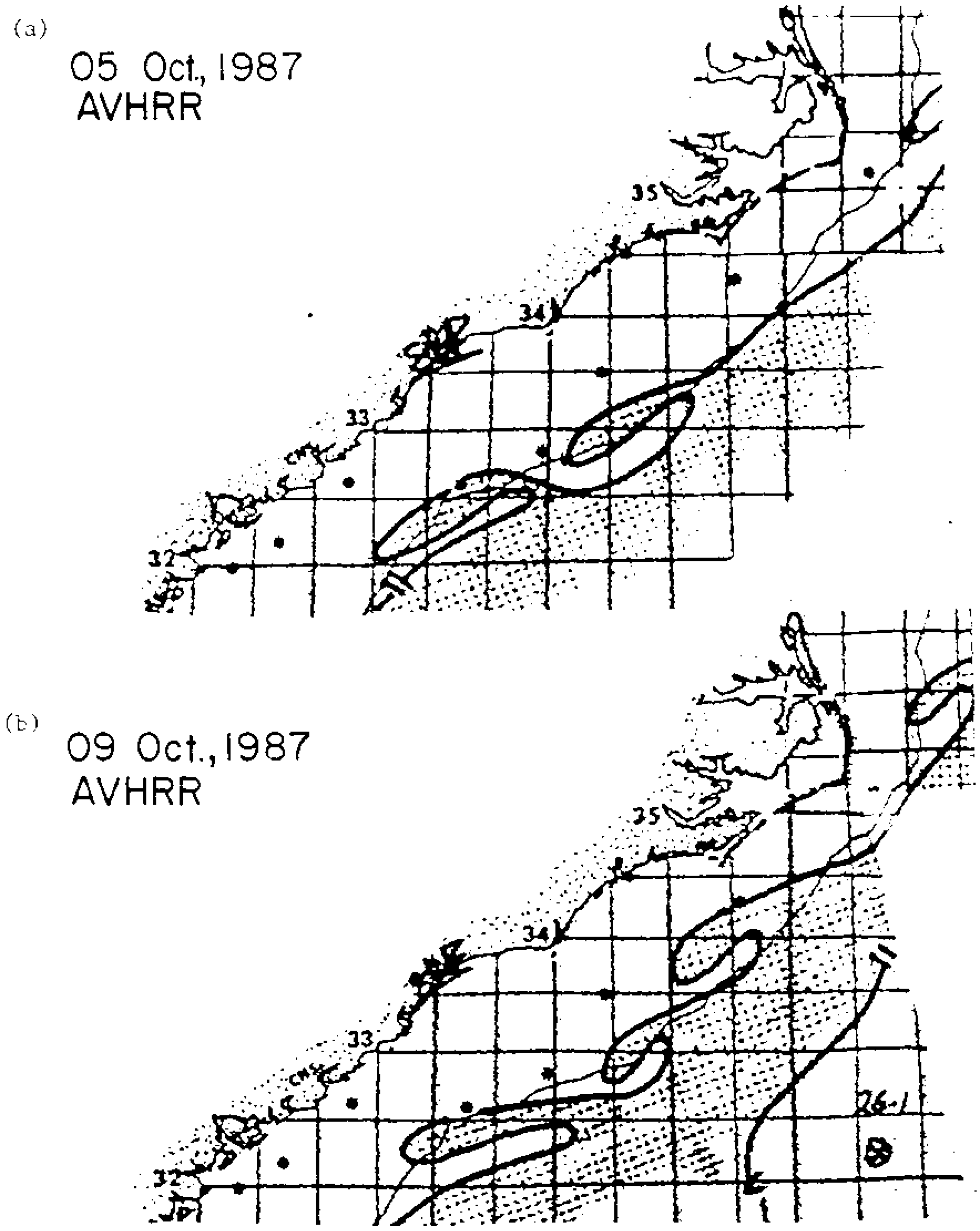


Figure 8. Satellite-derived sea-surface temperature field (detected by an infrared, Advanced Very High Resolution Radiometer sensor) depicting Gulf Stream frontal features (filaments) on (a) Oct. 5, 1987 and (b) Oct. 9, 1987. Carolina Capes coastline is to upper left and warm Gulf Stream waters are speckled.

dynamics in the Carolina Capes. The tide on the North Carolina coast consists of two principal constituents, the near semi-diurnal, with a principal period of 12 hours, and 25 minutes and the diurnal of 24 hours. The net result is that a parcel of water subjected to only the tides would traverse clockwise around an ellipse with a major axis of 2 km and a minor axis of 1 km. The net result would be that every 12 hours and 25 minutes, a parcel would end back up where it started. Therefore, the tide is discounted as having been the agent responsible for moving the dinoflagellates across the shelf. We now turn to the wind as the possible culprit.

Consider Figure 9. The wind field as observed by the National Weather Service at the Cape Hatteras Lighthouse station is plotted from Sept. 1 through Dec. 31, 1987. The wind's velocity vector, i.e. wind speed and direction, is measured and recorded every three hours. The Cape Hatteras wind vector time series data was chosen since no meteorological buoy data were available (from the region) for the period. The Hatteras winds were deemed more representative of outer shelf Onslow Bay wind conditions than were winds from Wilmington or Beaufort, N.C. Weisberg and Pietrafesa (1983) found that in the Carolina Capes, wind speed increases from 1.5 to 2.5 times in magnitude along the coastal mainland to several tens of kilometers offshore due to the larger boundary layer drag created by land vs. that of water, which slips with the wind. The net result is that the effective wind stress over water is 2.5 to 6.5 times larger than that over land, albeit in the same direction. Cape Hatteras winds are less affected by the frictional boundary layer created by the mainland, because they are collected on a barrier island more than 20 kilometers away from the mainland and are thus deemed more representative of actual over-the-water winds.

From Figure 9 we see that the wind field appears to fluctuate over periods

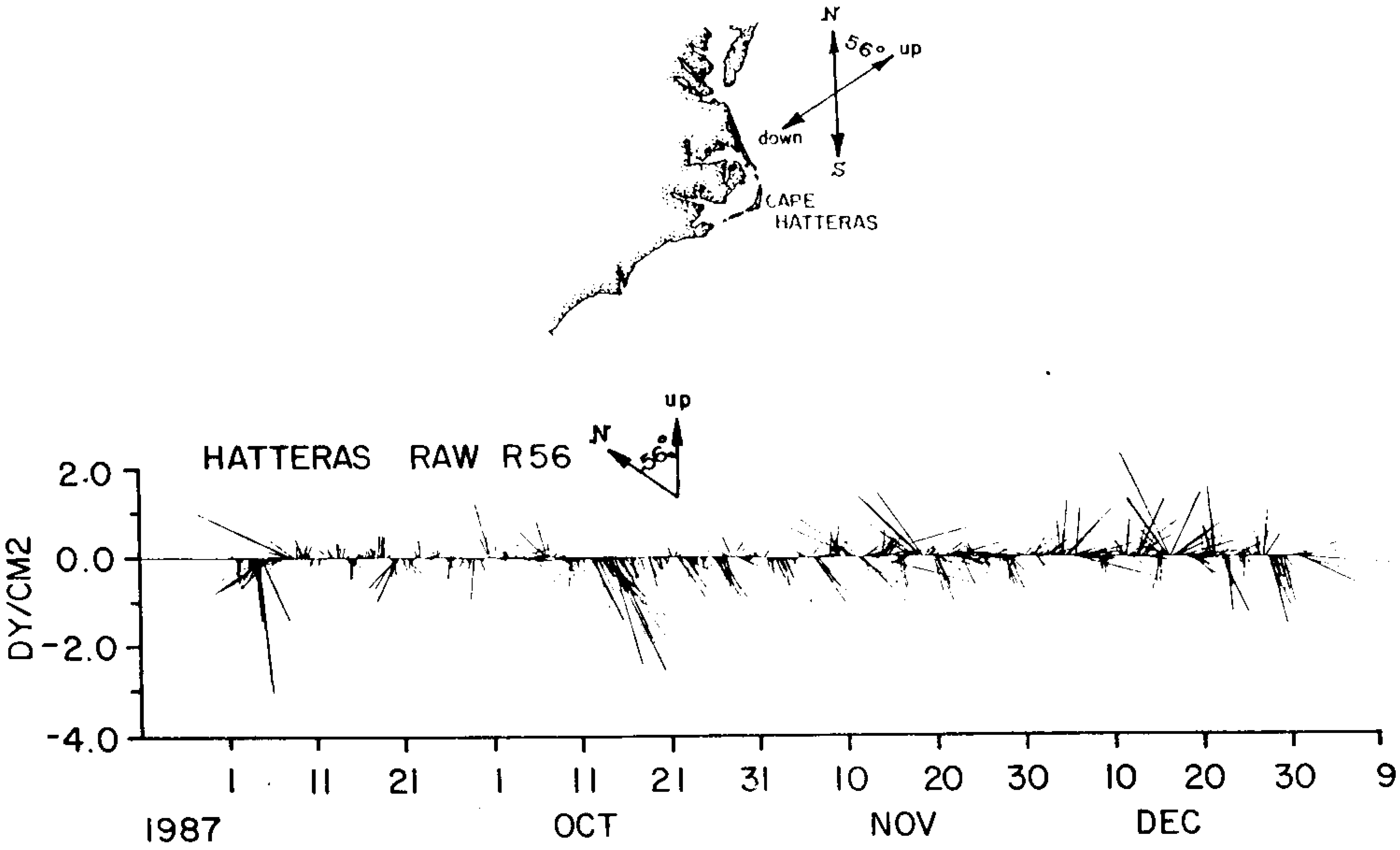


Figure 9. Windstress vectors created from wind velocity vectors measured every 3 hours at Cape Hatteras during the period Sept. 1 - Dec. 31, 1987. Vectors are pointing in direction towards which wind is blowing. Negative windstress vectors will mechanically drive the surface layer of water toward the Carolina Capes coast (see text for discussion).

of several days or more. In fact, a power spectrum of the energy of the wind field (not shown) suggests that the important energy bearing periods are between two days to two weeks. This means that the basic dynamic balance relating the onshore-offshore component of the flow field in the upper part of the water column can be described by invoking conventional Ekman theory. This theory states that the onshore-offshore (diabathic) mass flux, M_x, in the surface layer, D, is related to the alongshore (parabathic) component, τ^y, of the total windstress vector, $\vec{\tau}$, as

$$M_x = \frac{\tau^y}{f} \qquad (1)$$

where: $M_x = \int_0^D \rho u dz$, ρ is the water density, u is the diabathic water velocity vector components and f is the local Coriolis frequency. Note that this relationship states that the net transport of the wind driven surface layer will be directly onshore if the wind is blowing from the northeast. This surface layer will be of the order of 5 to 25 meters thick as a function of wind speed, vertical density gradient and vertical velocity gradient on the North Carolina shelf. A conceptual picture of the process is shown in Figure 10. A positive τ^y (a northeastward wind) yields a positive M_x (surface layer transport to the southeast), and a negative τ^y (a southwestward wind) yields a negative M_x (surface layer transport to the northwest).

From Figure 9 we see clearly that the wind field reverses its direction every few days from Sept. 4 through Oct. 8. Then, from Oct. 9 through Nov. 9, the wind velocity vector is directed towards the southwest to south sector with

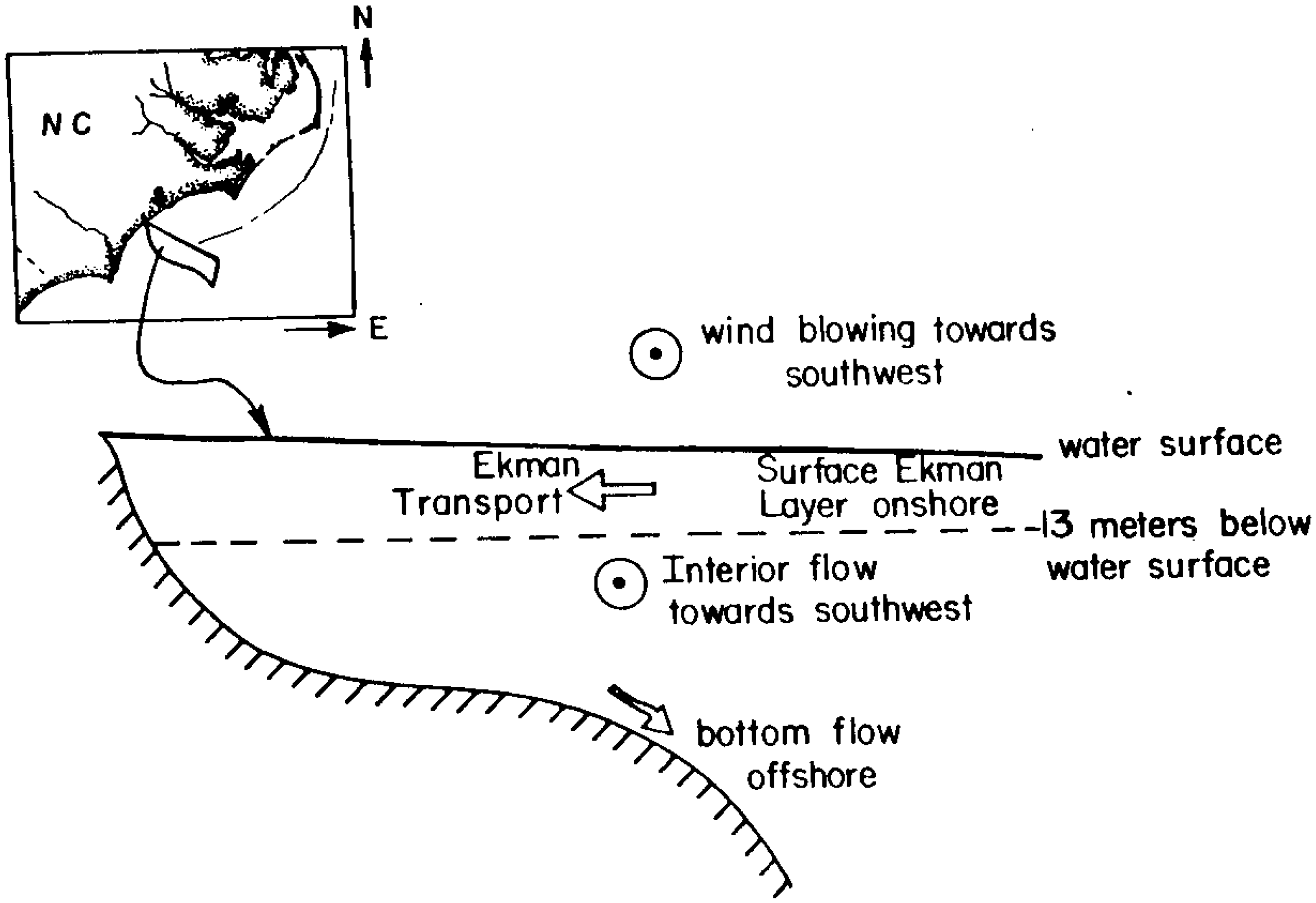


Figure 10. Vertical cross-section of the flow field on the Carolina Capes shelf by a wind blowing towards the southwest. The surface layer transport is 90° to the right of the wind or towards the northwest.

essentially no reversals. During Oct. 12 - 18, the winds are especially strong towards the south-southwest. On Nov. 8 the winds switch to become northeastward to northward.

Over the entire 19- day period, Oct. 9 - 27, the mean τ^y, alongshore windstress component was about 0.75 dynes/cm^2, which given previous results in the same region (Wittman, 1982), suggests a surface Ekman layer, D, of approximately 12 to 15 m thick and a vertically averaged onshore Ekman layer speed of approximately 6.3 cm/sec (or 5.5 km/day). During this period, the distance that water parcels and passive drifters would have moved across the shelf in the surface layer is about 105 km (65 mi) (Figure 11).

To calculate the total trajectory, Δx, of a water parcel located in the surface layer requires that we integrate the vertically averaged (mean) onshore velocity component over time, i.e.

$$\Delta x = \int \bar{u}\, d\, t = \int_{08\ \mathrm{Oct}}^{27\ \mathrm{Oct}} \frac{\tau^y}{fD}\, dt \qquad (2)$$

This calculation is shown in Figure 11. So as not to misrepresent the results shown in Figure 11, we note that between Sept. 1 and Oct. 7, winds are favorable for an onshore transport total trajectory, Δx, of about 28 km (17.4 mi) or about 750 meters/day versus a transport of 5,525 meters/day during Oct. 9 - 27. To see the net effects of the windfield after Oct. 8, simply zero out Δx and restart the calculation as given in equation (2) with the lower limit (or onset) of the time integration set at Oct. 8 (as shown). The tacit assumption is that the system has no memory of events prior to the onset. In other words, we zero out Δx at Oct. 8.

Between Oct. 8 and 12, parcels in the surface layer were driven by a weak southwestward wind about 8 km (5 mi) across the shelf at 1.6km/day. However,

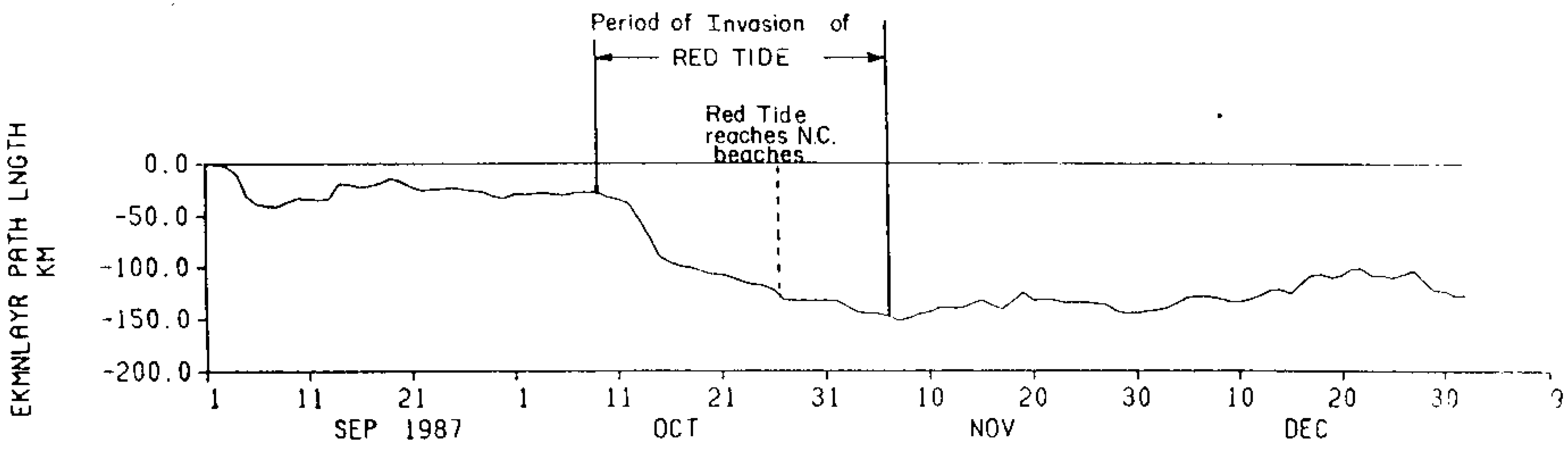


Figure 11. Across-shelf particle pathway of a parcel of water in the upper 13 meters (~40 feet) of the water column in Onslow Bay during the period Sept. 1 - Dec. 31, 1987. Negative values indicate an onshore transport.

during Oct. 13 - 16, the wind blew towards the SSW with an effective stress of between 1 to 3 dynes/cm^2, causing an onshore displacement of the surface layer of some 52 km (32 mi), about 13km/day. By Oct. 19, the surface layer had moved an additional 16 km (10 mi) shoreward driven by the southwestward winds of 0.3 to 0.5 dynes/cm^2. At this point, a passively drifting, buoyant particle imbedded in the Gulf Stream frontal filament prior to Oct. 8 would have traversed some 76 km (47 mi) across the shelf. To evaluate the possibility of this having occurred, we check the AVHRR imagery of Oct. 19.

In Figure 12, the sea-surface temperature map created by S. Baig of AOML via satellite infrared sensor data is shown. It appears that the entire Gulf Stream Front system of three filaments, which were present on Oct. 9 (Figure 8b) were subsequently advected onshore. The thermal frontal feature located in mid-shelf waters suggests that frontal waters which 10 days previous were part of three filaments now blanket the mid to outer shelf of the three bays. Amazingly the warm-water front appears to have maintained its general outline, essentially intact, from ten days earlier. From a comparison of Figures 8b and 12, it is clear that the warm water boundary defining the filament front has moved some 70$^+$km across the shelf. This agrees well with the model results.

During Oct. 17 - 27, the surface layer is advected another 26 km shoreward. By the latter date, the first warm water parcels that were mechanically detached from the Gulf Stream 19 days earlier would have reached the shoreline of mid Onslow Bay. By Oct. 31, the entire Onslow Bay coastline could have been invaded by filament waters. Then, from Oct. 31 to Nov. 7, the southwestward winds would have blown an additional water mass 18 km wide in the onshore/offshore direction and 13 m thick towards the coast. In all, a block of water 100 km wide in the longshore direction, 13 m thick in the vertical and 163

19 Oct., 1987
AVHRR

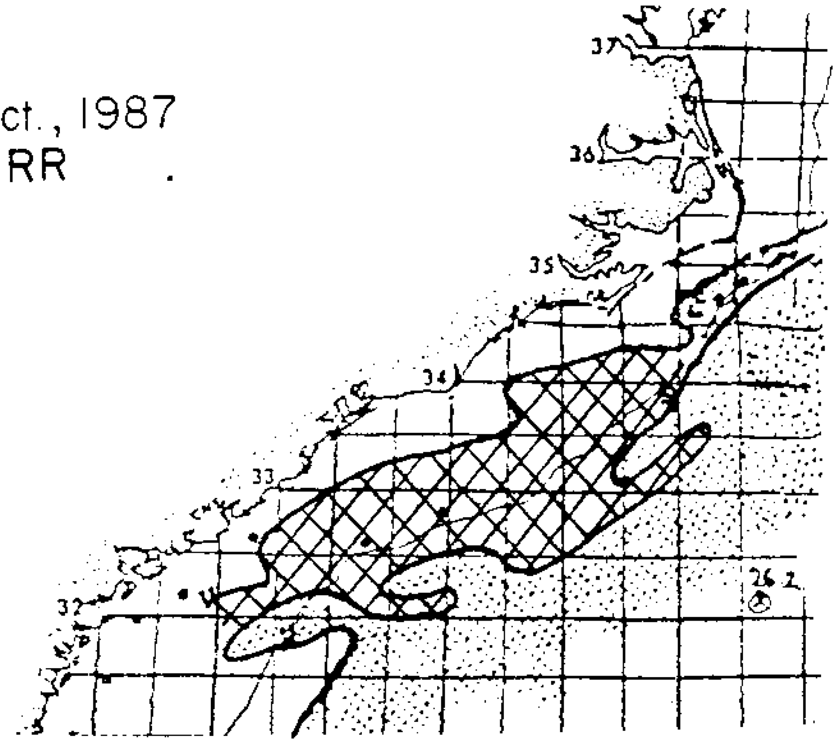


Figure 12. AVHRR satellite sea-surface temperature image on Oct. 19, 1987, depicting cross-shelf transport of water masses which were formerly part of the Gulf Stream on Oct. 9. Gulf Stream (proper) waters indicated by speckled area. Previous Gulf Stream frontal waters indicated by hatched area.

km wide in the cross-shelf direction moved across Onslow Bay coastal waters over the 30-day period. So, every day, on the average, a block of water 40 feet thick, 62 miles long and 3.3 miles wide was advected towards the coast. At least 12 of those blocks actually reached the shore.

IV. 1987: An Atypical Year?

Were conditions during the fall of 1987 sufficiently atypical so that the mixture of winds and filament presence were unusual? To address this question, we assess the windfield, particularly the alongshore windstress component, $-\tau^y$, compute a Δx or shoreward particle transport trajectory plot and check for the serendipitous presence of Gulf Stream frontal filaments. Clearly if the 1987 red tide recruitment scenario were to have been singular, then during previous years, either the winds did not blow southwestward for a sufficiently long period of time or with a large enough magnitude, or no filaments were present. There is one other possibility: the filaments were not laden with buoyant Ptychodiscus brevis dinoflagellates. In other words, the loading of the Loop Current and hence the Gulf Stream as occurred off Naples, Fla., in Aug. 1987 was a singular case.

Consider Figures 13 and 14. In figures 13 a - h the windstress vector component in the longshore direction (τ^y) is presented for the years 1979 to 1986. In figures 14 a - h the cross-shelf particle trajectory path lengths are computed. The years 1979 and 1980 are poor recruitment years. Parcels located at the shelfbreak, either within or without filaments in the Carolina Capes, would not have been transported to the beach in the wind-driven surface layer. However, this is not the case for the years 1981 to 1986. In 1981, a parcel could have been transported 135 km between Oct. 9 and Nov. 14. In 1982, the surface flow is shoreward nearly the entire period of Sept. 4 to Dec. 15. In 1983, the flow is shoreward between Sept. 24 to Oct. 23. 1984 is very similar to 1982. For

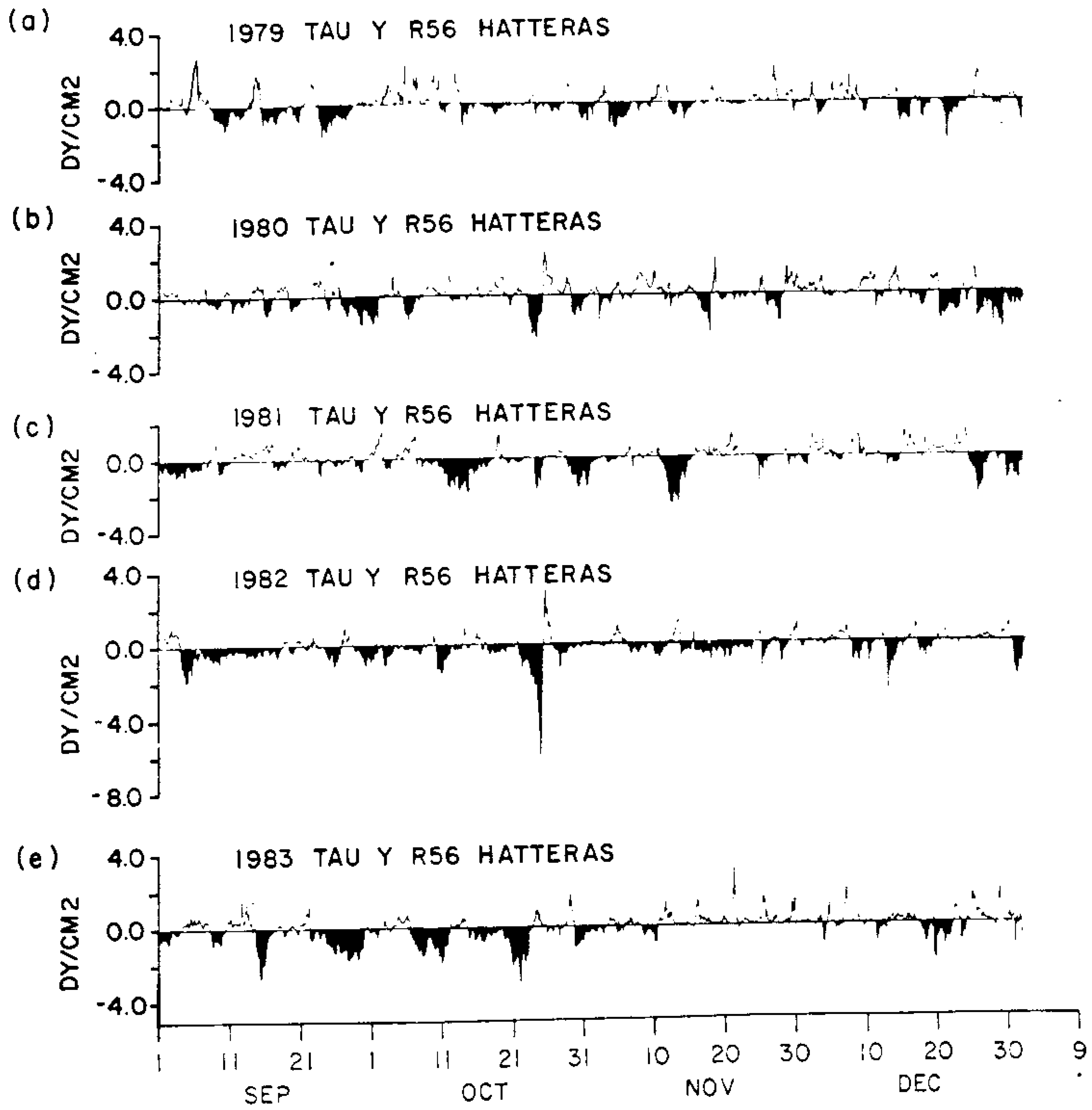
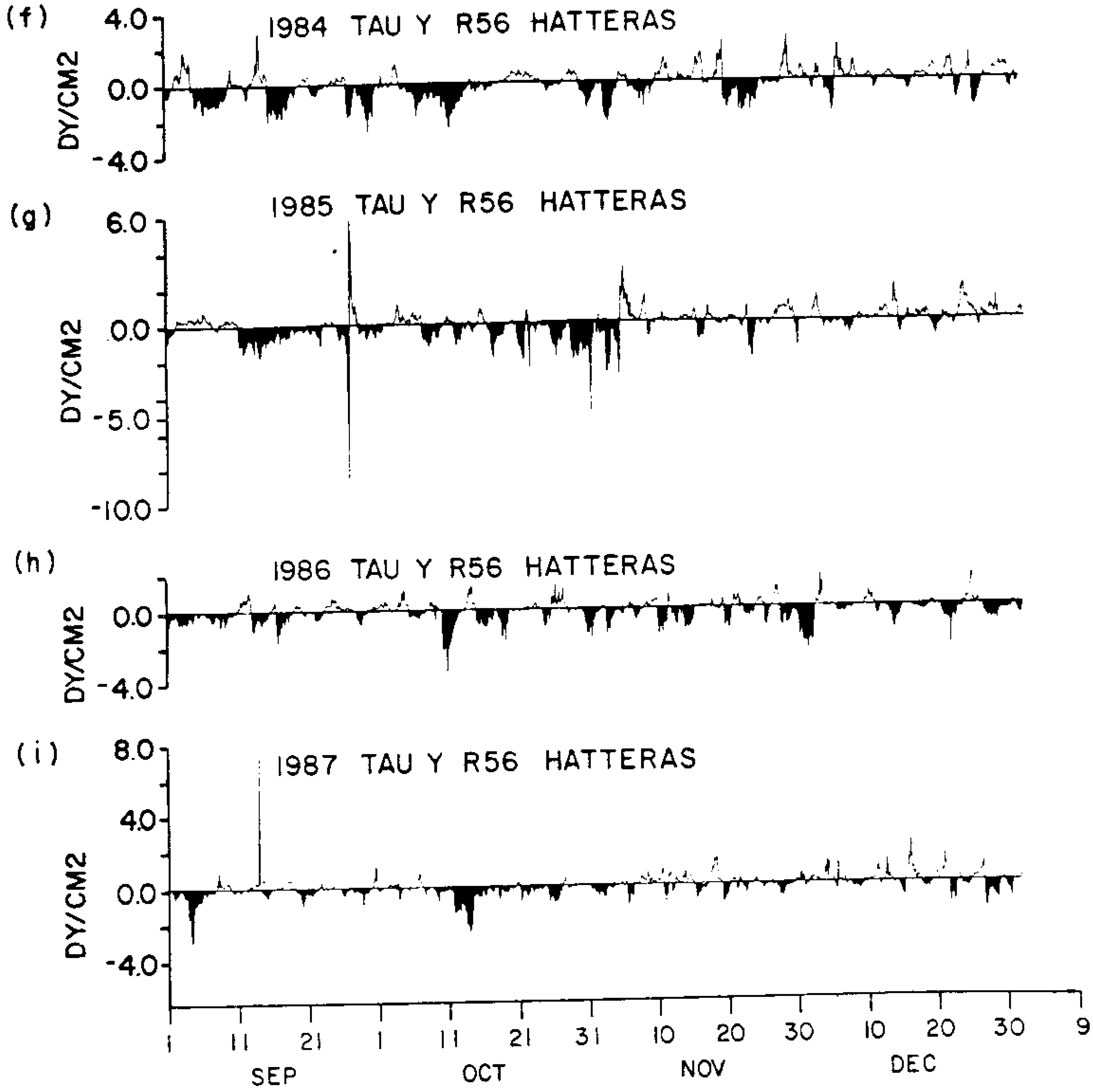


Figure 13. Alongshore component of the 3 hourly windstress measured at Cape Hatteras during the months of Sept. - Dec. over the years 1979 to 1987 (a through i respectively). A negative (-) τ^y is a windstress component towards the southeast, and a (+) τ^y is to the northeast.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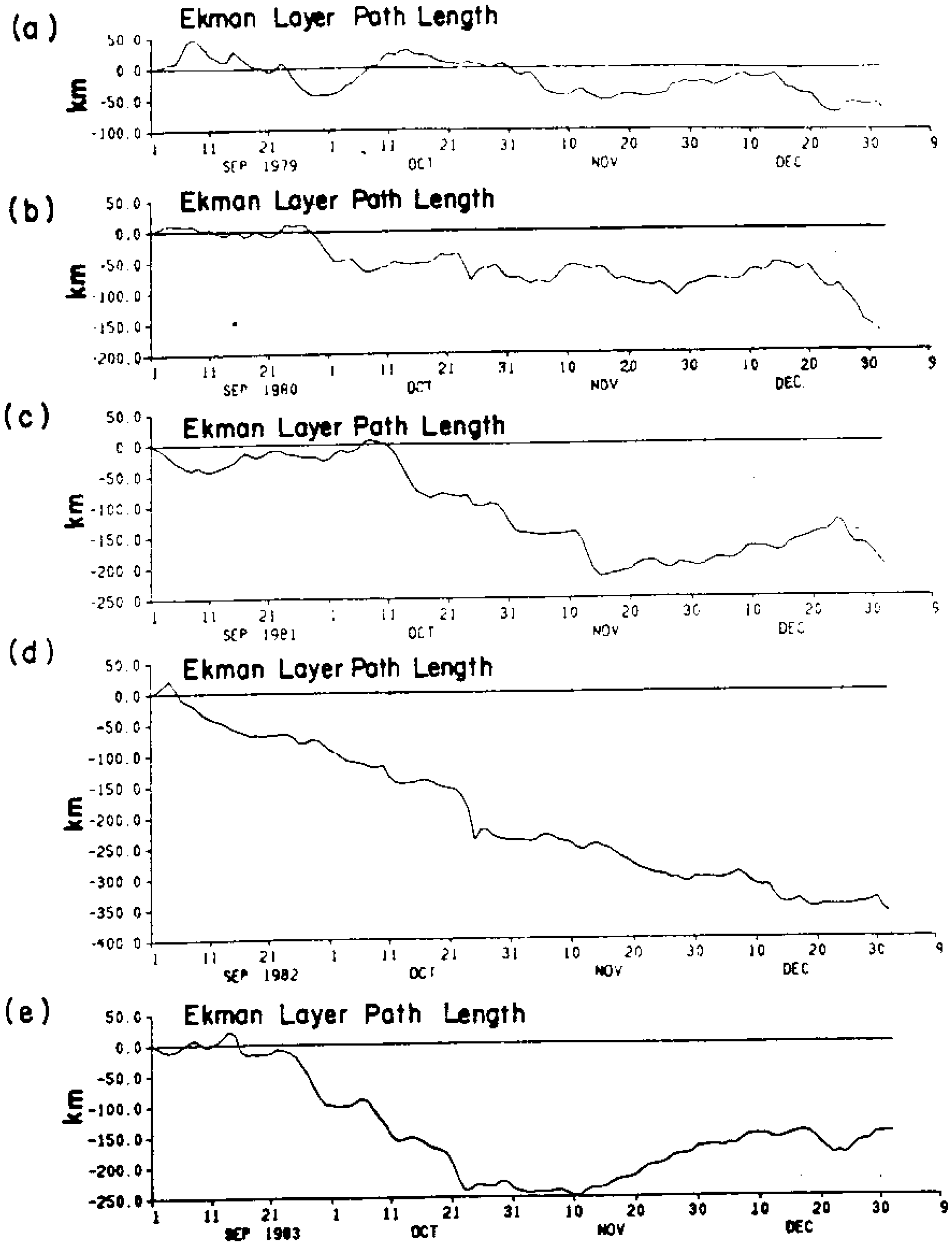
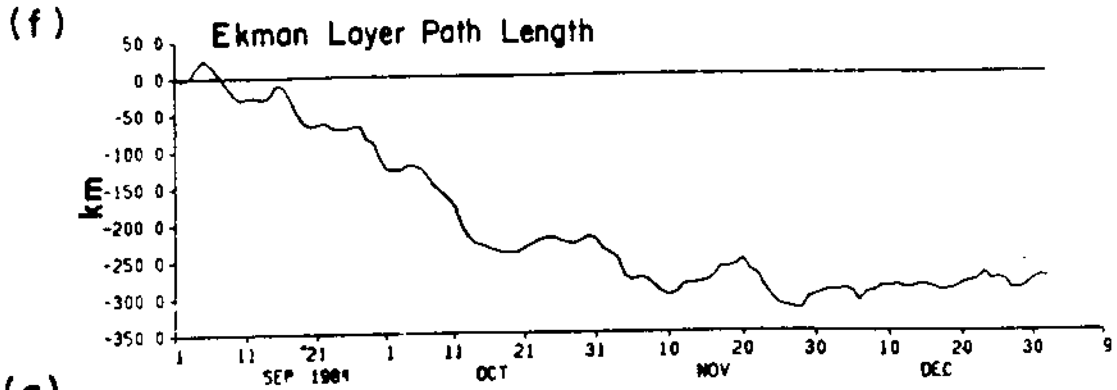


Figure 14. Wind-driven onshore/offshore transport of the surface layer of water on the Carolina Capes shelf during the period Sept. 1 - Dec. 31 for the years 1979 to 1987 (a through i respectively). Negative values indicate a shoreward movement of water parcels.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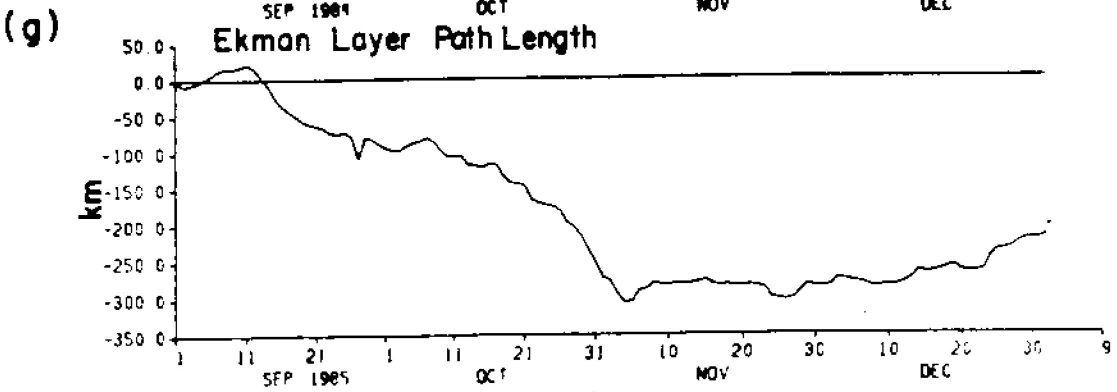
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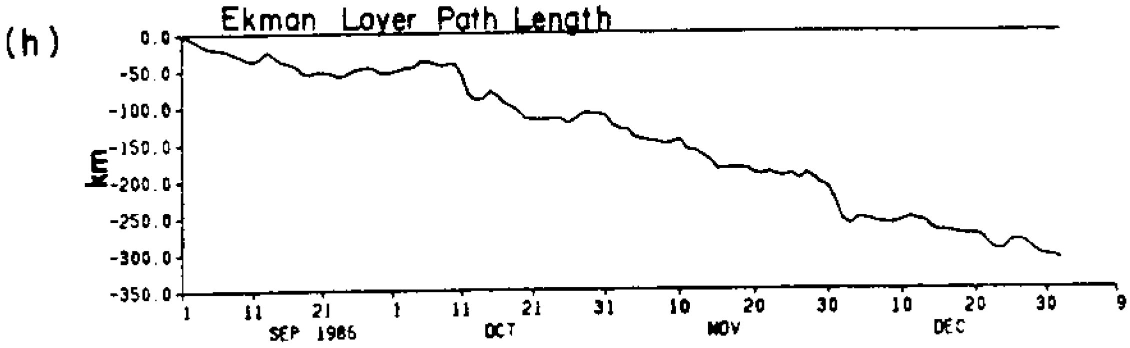
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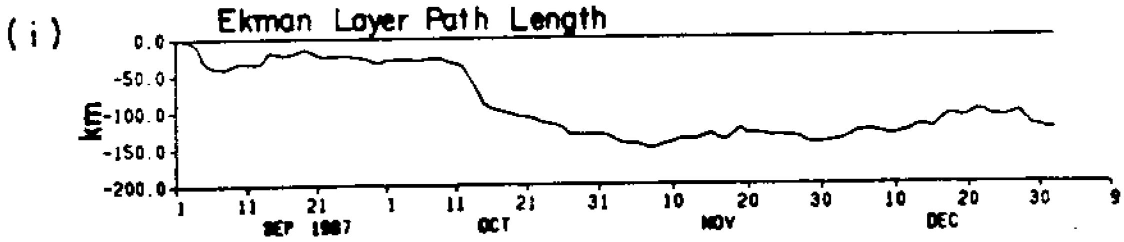
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20
30
9
SEP 1987
OCT
NOV
DEC

1985, the flow is strongly shoreward from Sept. 15 to Nov. 3. And in 1986, favorable surface recruitment occurs from Oct. 10 to Dec. 31. Revealing statistics for the individual years are presented in Table 1. It appears that over the previous eight years, two were worse, three were at least equal to and three were better than 1987 for a similar recruitment of the red tide dinoflagellate; were it present in a frontal filament. So if 1987 is the standard, then 78 percent of the nine year period was favorable for red tide dinoflagellate infestation and 1987 was typical by surface Ekman flux conditions. Then, why was 1987 the only year in recorded history in which the red tide was actually noted to be present in NC coastal waters? There are several possibilities.

It is possible that persistent southwestward winds and a nearby frontal filament are not the only conditions necessary for red tide recruitment. Perhaps the windstress vector must exceed some minimum value, say for example 1.5 to 2 dynes/cm^2, for several days to actually remove water masses (and the dinoflagellates) from a frontal filament as may have occurred during Oct. 13 - 16. This sort of wind eruption event would require that additional southwestward winds follow for at least 10 to 14 days. This wind scenario occurred in years 1981,1982, 1983, 1984, 1986 and, of course, 1987. In Table 2, we relate the "extreme" wind cases with the contemporaneous presence of Gulf Stream Front filaments. The joint occurrence of a southwest wind and a filament should be a limiting factor since the odds on the conjunctions of both a "large" southward windstress followed by at least moderate to light southwestward winds while a filament is present seem prohibitive. However, remarkably in every "extreme" wind case, a filament is present. Moreover, in all of the cases, the filaments initially grow in length and become detached from the Gulf Stream Front to become a warm water mass being advected towards the coast. Figures 15 a, b

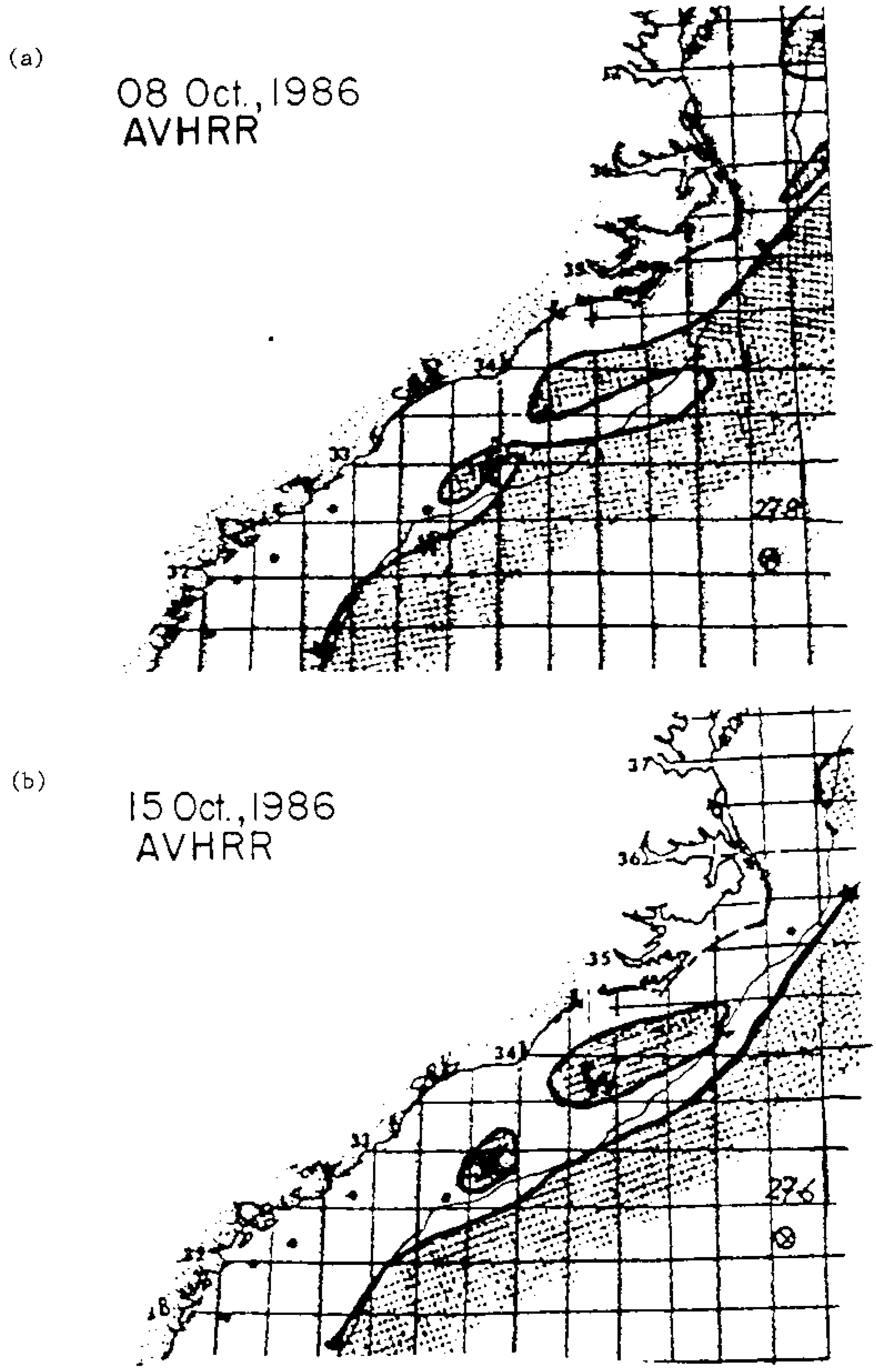

Figure 15. Wind forced detachment of two Gulf Stream frontal filaments to create two isolated warm water masses. Frontal filaments were visible on (a) Oct. 8 in AVHRR imagery, subjected to southwestward winds from Oct. 9 - 12 and appear as divested pools of Gulf Stream water (b) Oct. 15.

demonstrate this scenario.

It is of note that frontal filaments are frequently present offshore of the Carolina Capes. Pietrafesa (1978) estimated from AVHRR satellite imagery that during the 24-month period 1976 to 1978, a different filament was present every 10 days in Onslow Bay. Since these features are typically 125 to 250 km long and travel with 30 to 50 cm/sec phase speeds, then it takes four to six days for an individual filament to pass by Onslow Bay. So, the odds are at least 50/50 that a filament will be present at any particular time off Onslow Bay. Still, it is peculiar that from 1981 to 1987, the 16 "extreme" southwest wind cases that occurred from September to November were all accompanied by filaments. Perhaps Pietrafesa's 1976-78 findings were a lower limit on the frequency of occurrence of these ubiquitous features.

There is also the distinct possibility that the red tide dinoflagellate has never reached North Carolina coastal waters previously. Since the sources of the red tide are to the south, then either it is an unusual phenomenon for the Gulf Stream to be seeded or when seeded, the dinoflagellate likely exits off the east coast of Florida via the same mechanisms described above. In fact, red tide outbreaks have been noted off the east Florida shelf (D. Kamykowski, personal communication). If this is true of Florida, then why has North Carolina or South Carolina never had an outbreak in the past? The answer would seem to be that every previous load of red tide coming from the west Florida shelf has been dumped onto the east Florida shelf via the mechanism of occurrence of southward winds off the east Florida shelf.

In 1987 when the filaments carrying the red tide dinoflagellate passed by Florida Sept. 6 - 12 (National Weather Service), the east Florida mean winds were from the south and southeast. These winds would have driven the surface layer offshore. At this time of year the more typical condition on the east Florida coast is for winds to be directed towards the west, accompanied by offshore transport of the surface waters (Hastenrath and Lamb (1977). The 1987 case could have been a singular case. The red tide load may more typically be dumped on the Florida shelf never to reach downstream.

Another theory (D. Kamykowski, personal communication) is that the dinoflagellates have been lying dormant at the bottom of Onslow Bay and simply needed the right oceanic weather conditions to cause a plant bloom. The ocean weather that might cause such a bloom are warm nutrient-rich waters such as might be derived from a detached filament. Of course this scenario would have required the dinoflagellates to have been seeded in 1986. If the seeding occurred prior to 1986 and after 1979, then surely one of the 15 filament-wind cases presented in Table 2 would have triggered a bloom in an earlier year.

Finally, perhaps the Gulf Stream system had never been loaded with red tide dinoflagellates previous to 1987, an unlikely possibility.

V. CONCLUSIONS

The red tide outbreak of 1987 was disastrous to the North Carolina shellfish industry. Although this appears to have been a singular event in remembered history, it is entirely possible that it happened previously to some lesser degree and moreover that it could happen again. The most plausible theory of how the given phenomenon occurred are based on a series of marine hydrodynamic conditions that occurred in a sequence. First, the presence of a meteorological high pressure system on Aug. 24 allowed the red tide organism to be loaded into the Loop Current and subsequently carried around the Keys and into the Florida Straits where the Loop Current extension joins the Gulf Stream. Then, because of prevailing northward winds associated with an atmospheric low pressure system, the dinoflagellates were not allowed to exit the Gulf Stream onto the east Florida shelf. Next, the dinoflagellates were advected in the Gulf Stream Front northward past the Charleston Bump, where several Gulf Stream frontal unstabilities were enhanced to become large amplitude filaments propagating northward. Finally, as the filaments passed by Onslow Bay, an energetic southwestward wind was present and it simply advected the warm red tide dinoflagellates laden surface waters of the warm tongue of the filament, as well as the nutrient rich upwelled waters below and offshore of the filament, across the shelf and onto the beaches. The scenario is summarized in Figure 16

In the photograph on the following page, AVHRR imagery of seasurface temperature in Onslow Bay on Oct. 5, Oct. 19 and Nov. 2 are presented. The top image indicates the presence of a well defined Gulf Stream frontal filament, unaffected by wind, on the outer shelf on Oct. 5. The middle picture shows a diffuse, wind driven Gulf Stream frontal water mass extending two-thirds of the way across the shelf. The bottom image, taken on Nov. 2 suggests total innundation of the Onslow Bay shelf by Gulf Stream frontal water.

In conclusion the possibility of a future outbreak of the red tide in North Carolina coastal waters hinges on the sequential occurrence of a set of specific biological, meteorological and physical oceanographic conditions. Since the marine hydrodynamic conditions present off North Carolina in the fall of 1987 were typical, then we must turn to the east and west coasts of Florida for our answer. Since red tide outbreaks are a common occurrence on the west Florida shelf then we assume that conditions there are a contributory factor. However, as the mean August winds over lower Florida are northwards, a dinoflagellate outbreak would not normally be swept into the loop current. The occurrence of a high pressure system over the northern Gulf of Mexico coupled with a

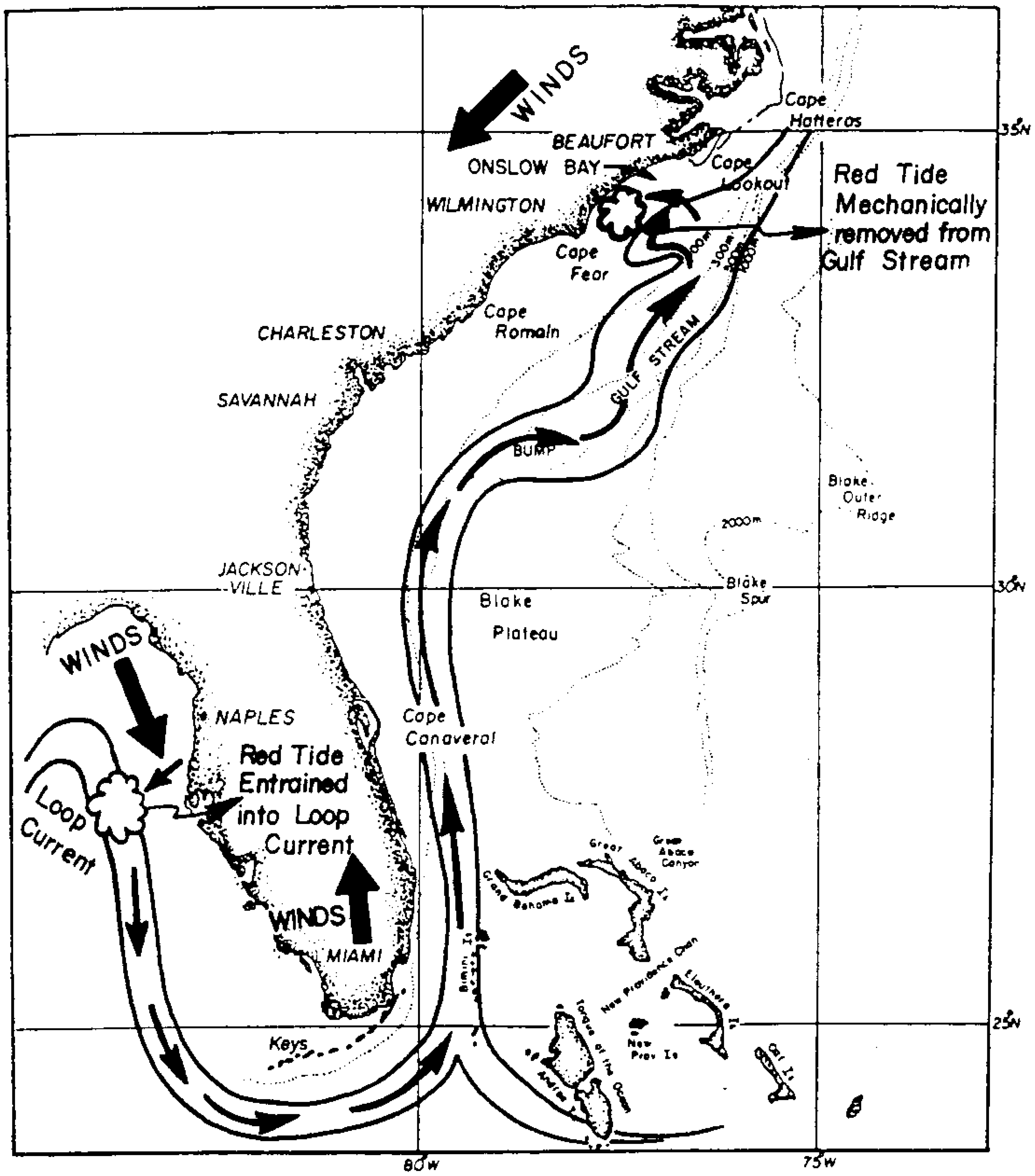

Figure 16. Pathway ⟶ of red tide ☁ dinoflagellate from Naples, Florida to Onslow Bay, North Carolina, with prevailing winds ➡ during respective periods of appearance of red tide off Naples, Miami and Onslow Bay.

dinoflagellate outbreaks on the south Florida Gulf coast appear to be essential to red tide outbreaks on the N.C. coasts.

VI. RECOMMENDATIONS

Recommendations for the future are that

(a) whenever red tide outbreaks occur on the west Florida shelf, we dutifully note the date of outbreak,

(b) monitor both the winds off of both of the west and east coasts of Florida over the next 10 to 20 days and wait for reports of an east coast Florida outbreak or the lack thereof, and

(c) monitor both Gulf Stream frontal filaments via AVHRR Satellite imagery and coastal winds.

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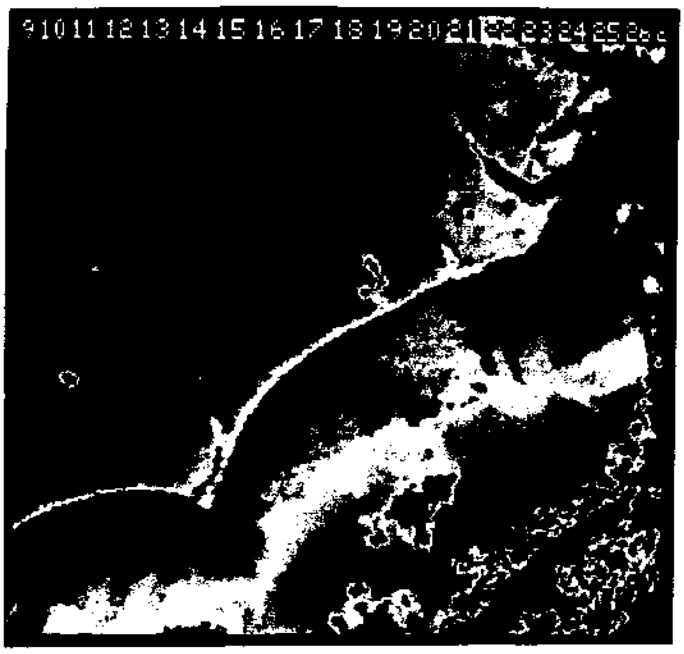

9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26

TABLE 1

	Periods of prolonged (>5 days) southwestward wind	Longest Continuous across-shelf particle trajectory Distances in km (mi)	Vertically averaged onshore surface layer speeds cm/sec (km/day)	"Better" (B) Equal" To (E) or "Worse Than" the 1987 year for DF recruitment
1979	NONE	48 (30)	–	W
1980	NONE	82 (51)	2.4 (2.1)	W
1981	10/10 - 11/14	225.6 (140)	6.4 (5.6)	E
1982	9/04 - 12/15	368 (228)	7.4 (10.2)	B
1983	9/24 - 11/12	272 (169)	11.8 (13.1)	B
1984	9/06 - 11/10	347 (215)	10.2 (8.8)	E
1985	9/10 - 11/03	328 (203)	14.2 (12.3)	B
1986	10/10 - 12/31	310 (192)	3.8 (3.2)	E
1987	10/09 - 10/27	105 (65.1)	6.3 (5.5)	Standard
	10/09 - 11/07	126 (78.1)	4.3 (3.8)	

TABLE 2

OCCURRENCES OF "EXTREME" SOUTHWESTWARD WINDS FOLLOWED BY SW WARD WINDS

Year	Period	Filament Present
1981	Oct. 11 - 15	yes
	Oct. 28 - Nov 2	yes
	Nov. 13 - 18	yes
1982	Oct. 23 - 27	yes
1983	Sept. 24 - 30	yes
	Oct. 6 - 12	yes
	Oct. 21 - 24	yes
1984	Sept. 16 - 21	yes
	Sept. 27 - Oct. 2	yes
	Oct. 11 - 14	yes
1985	Sept. 13 - 16	yes
	Oct. 14 - 15	yes
	Oct. 28 - Nov. 01	yes
1986	Oct. 11 - 14	yes
	Oct. 19 - 21	yes