Chapter

On the Possibility of Non-Local and Local Oil Spills Striking the Shores of North Carolina and South Carolina

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Abstract

Oil spills, the releases of liquid petroleum hydrocarbons into the marine environment, have occurred in the Gulf of Mexico (GOM) of the United States (U.S.A). However, no oil spills have ever affected the Eastern Atlantic Seaboard (EAS) of the U.S.A. Nonetheless, we demonstrate from data and numerical modeling that oil spills in the GOM have the potential to reach the U.S.A. EAS via a combination of atmospheric storms, major ocean currents and atmospheric wind driven surface currents. The basis for this hypothesis is that in August of 1987, a Karena Brevis toxin plant outbreak occurred in the GOM, and several weeks hence, showed up on the shores of North Carolina and South Carolina. We recreate that environmental scenario employing atmospheric and oceanic data from 1987, Sea Surface Temperature (SST) images, and via numerical modeling, that an atmospheric cold front, the combination of the Loop Current, the Florida Current, and Gulf Stream Frontal Filaments, created the pathways for the transport of K-Brevis plants from the Gulf to the U.S.A. EAS. Numerical model output of oil spill scenarios, both non-local in the GOM and local to the Carolinas, is presented to prove that this latter hypothesis has credibility and viability.

Keywords: cold fronts, K-breve, red tide, Loop Current, Gulf Stream, frontal filaments, mid-latitude cyclones

1. Introduction

Oil Spills have never been reported as having occurred along the coasts of either South Carolina (SC) or North Carolina (NC). However, we present evidence, by way of a surrogate to oil droplets; a marine-based toxic biological plant, where a non-local source invasion of oil could occur in the coastal waters of those states. Additionally, via numerical modeling, we show that both non-local and local spills could invade

SC and NC beaches. By way of example, an industrial disaster, the British Petroleum Oil (BPO) Company Deepwater Horizon oil spill, occurred in late April 2010 in the eastern Gulf of Mexico (GOM). The BPO vessel, the Macondo Prospect, sprung a leak that resulted in the largest marine oil spill in the history of the petroleum industry. In truth, the BPO oil spill was contained in the GOM. Therefore, a presumption could be that given the BPO spill in the GOM, that future spills will be contained in kind. That is not the case, given evidence provided by our surrogate GOM-based toxic marine plant.

On October 31, 1987, Onslow Bay, NC continental shelf waters became infested with a yellow-green toxic organism. Investigators from the National Oceanic & Atmospheric Administration (NOAA) National Marine Fisheries Service (NMFS) Laboratory in Beaufort NC (Dr. P. Tester, p.c.) determined that the yellow-green patches consisted of the one-celled plant organism Ptychodiscus Brevis or the Karina Brevis Dinoflagellate, and accompanying marine algae indigenous to tropical waters such as the GOM. The effects of the one-celled intruder were immediate and widespread. Shellfish, such as clams, scallops and oysters became infected and 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 surf fishers suddenly felt the sensations of burning eyes and lungs, nausea, and dizziness. Subsequently shell fishing was banned in NC and the beaches were closed.

Federal and university scientists became suspicious that the Red Tide dinoflagellate was transported to the subtropical waters of NC and SC from the tropical south. If so, then what was the source of the K-Brevis and what was its pathway? The answer was addressed by Pietrafesa et al. [1] in which it was hypothesized that an atmospheric cold front in the GOM in August, the Loop Current, the Gulf Stream, and the atmospheric wind field of NC in late September and early October created a hypothetical scenario for the realization of this event. Could it happen again? Possibly. Further, could GOM spilled oil, a non-local event for the Carolinas, be transported the same way as the Red Tide to NC and SC? Further, could oil spilled locally off the NC coast be transported to NC and SC beaches and estuaries? Conventional wisdom is that the oil would be swept to away by the Gulf Stream and distributed across the North Atlantic Ocean to the north. However, via numerical model experiments we show that NC spills could reach the beaches of NC and SC. We develop the physical descriptive and numerical modeling scenarios below.

In Section 2, we describe the 1987 eastern GOM Red Tide event that reached NC and SC beaches. In Section 3, we discount the Astronomical Tides as a potential cause of non-local or oil spills reaching the NC or SC beaches. In Section 4, we describe Gulf Stream Variability and Frontal Filaments. In Section 5, we revisit the 1987 Red Tide event that invaded NC and SC coastal waters, via satellite imagery and then numerically model the non-local Red Tide event with modern numerical modeling. In Section 6, we model hypothetical local oil spills on the NC coast during the passages of a GSF and a typical mid-latitude cyclone. Section 7 includes the conclusions and summary.

2. The 1987 Eastern Gulf of Mexico Red Tide Event

On August 24, 1987, a breakout of the Red Tide was reported off the coast of Naples, Florida, in the GOM. As the oceanic currents flow, Naples is approximately 1600 kilometers (1010 miles), from the coasts of the Carolinas. If the Red Tide plants were able to jump aboard the Loop Current in the Gulf of Mexico, they could have been transported down the west Florida coast, around the Florida Keys, through the Florida Straits where it would have become part of the westward flowing Antilles Current and then loaded into the northward flowing Florida Current, which then becomes the northward flowing Gulf Stream (**Figure 1**). From the east coast of Florida, the organism would have had to have traveled north reaching Onslow Bay NC and Long Bay NC/SC outer shelf waters sometime in early October. Let us first consider the conditions that were present at the time.

In **Figure 2a**, the NOAA National Weather Service (NWS) atmospheric pressure map for August 24, 1987 shows a high-pressure center located in the southeastern USA. The winds associated with this weather system on the west Florida shelf would have been to the south, thereby effecting an offshore transport of surface waters via an Ekman surface layer [3] from the shelf into the eastern side of the GOM Loop Current. Two weeks hence, we find a low-pressure center or atmospheric cyclone located in the southeast, as shown in the September 7 weather map in **Figure 2b**. The winds are to the north on the eastern Atlantic Florida shelf, thereby driving surface coastal waters offshore, again via Ekman surface layer dynamics [3, 4], into the Gulf Stream. Therefore, while the Red Tide organisms were likely in the area of the east Florida shelf, winds were unfavorable for onshore transport out of the western edge of the Gulf Stream and onto the shelf. Therefore, the organisms stayed in the Gulf Stream, on its western side, marching northward. They could have gone from the western side of the Gulf Stream via the Astronomical Tides or due to Gulf Stream–related phenomena. We investigate that further below in Sections 3, 4, and 5.

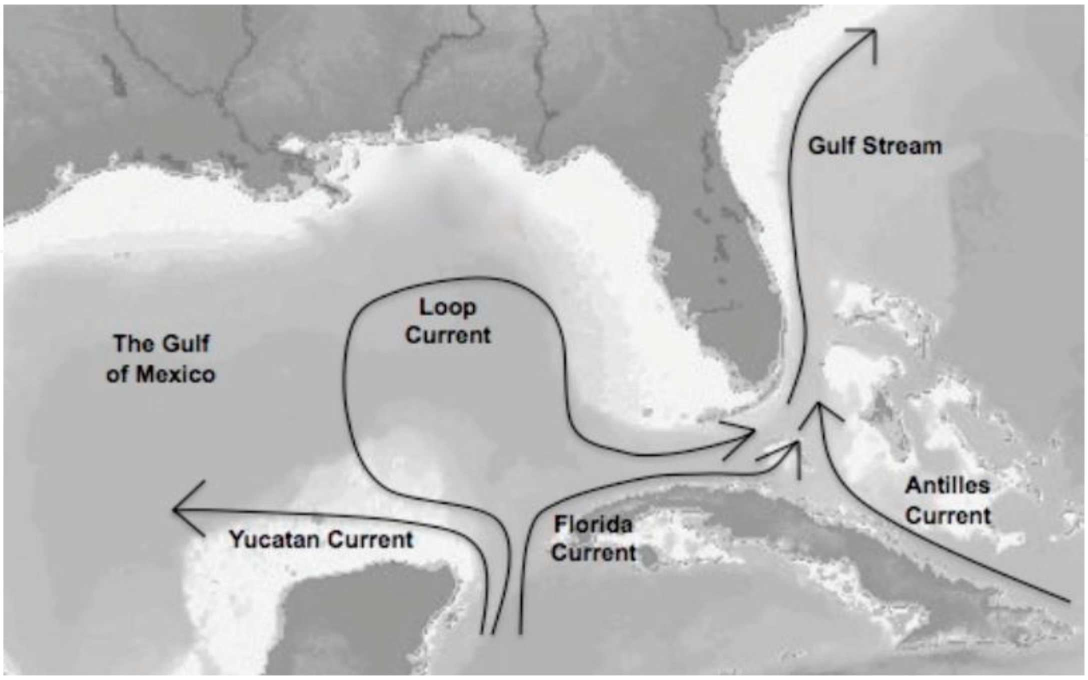
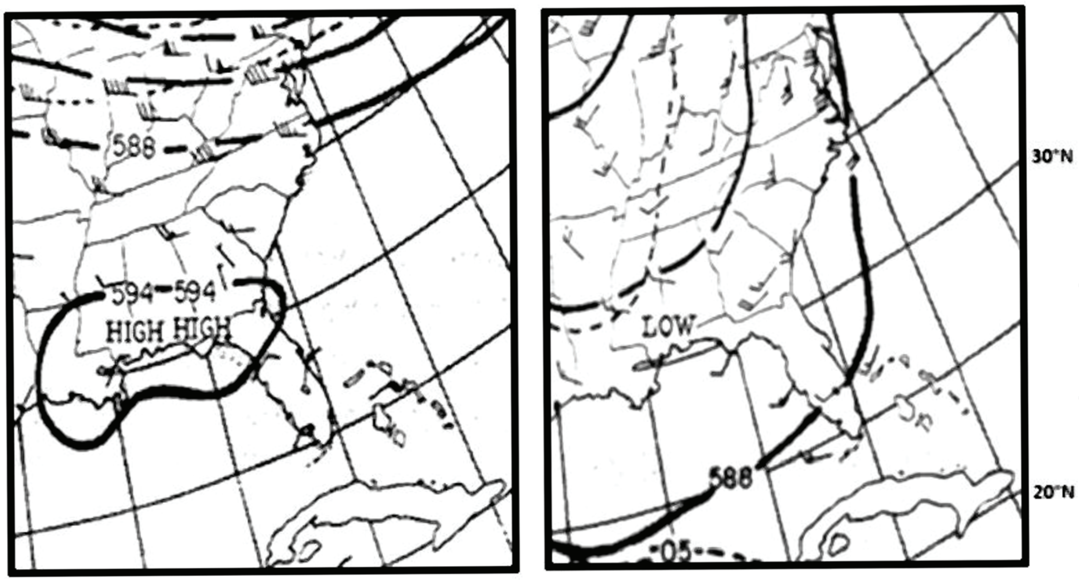


Figure 1.
The Loop, Antilles and Florida Currents, and the Gulf Stream (from [2]).



(a) (b)

Figure 2.
NWS 500 mb surface pressure maps. (a) Left image is August 24, 1987; (b) right image is September 8 1987. These maps are hard copies of those produced by the NWS and are copied with full fidelity.

3. Astronomical tides in the Southeast Atlantic

The astronomical tides of the Atlantic Ocean have been explored since ancient times. As early as 600 CE, medieval monks documented tidal changes throughout the coast of England, and they properly grasped the link between tides, the location of the sun, and the phases of the moon. The utilization of precise tidal gauges for continuous gathering data, as well as advanced computers for modeling and prediction, has greatly increased tide table accuracy and knowledge of the numerous constituent forces that shape and influence tidal behavior.

The tide in the S-shaped north-south Atlantic basin may indeed be conceived of as a unique phenomenon that acts like a massive standing wave traveling across the basin. A variety of complicated elements govern the pace, path, size, and behavior of the Atlantic tide, involving shoreline unusual features, seafloor topography, and dynamical patterns of wind and current. The most frequent and prominent tidal variety in the Atlantic Ocean Basin is the semidiurnal, which has two high and two low tides every tidal day (lasting about 24 hours and 50 minutes). Semidiurnal tides occur over the entire eastern edge of the Atlantic, as well as across the majority of North and South America. Mixed tides, or those with both diurnal (one high and one low tide per day) and semidiurnal oscillations, predominate in the Gulf of Mexico and the Caribbean Sea, as well as along the southeastern coast of Brazil and Tierra del Fuego, in some areas of the Mediterranean, and along the coast of Labrador; the only purely diurnal tides occur in portions of the Gulf of Mexico.

Tidal dynamics for the Southeast Atlantic continental margin have been thoroughly discussed in Pietrafesa et al. [5]. As such, the tide on the NC and SC coasts consists of two principal constituents, the near semi-diurnal, M2, with a principal period of 12 hours, and 25 minutes and the diurnal, S1, of 24 hours. According to that study, the M2 and S1 tides are both Poincare Waves. The net result is that a parcel of water subjected to only the tides would traverse clockwise around an ellipse with a major onshore-offshore axis of 2 km and a minor alongshore axis of 1 km. The net

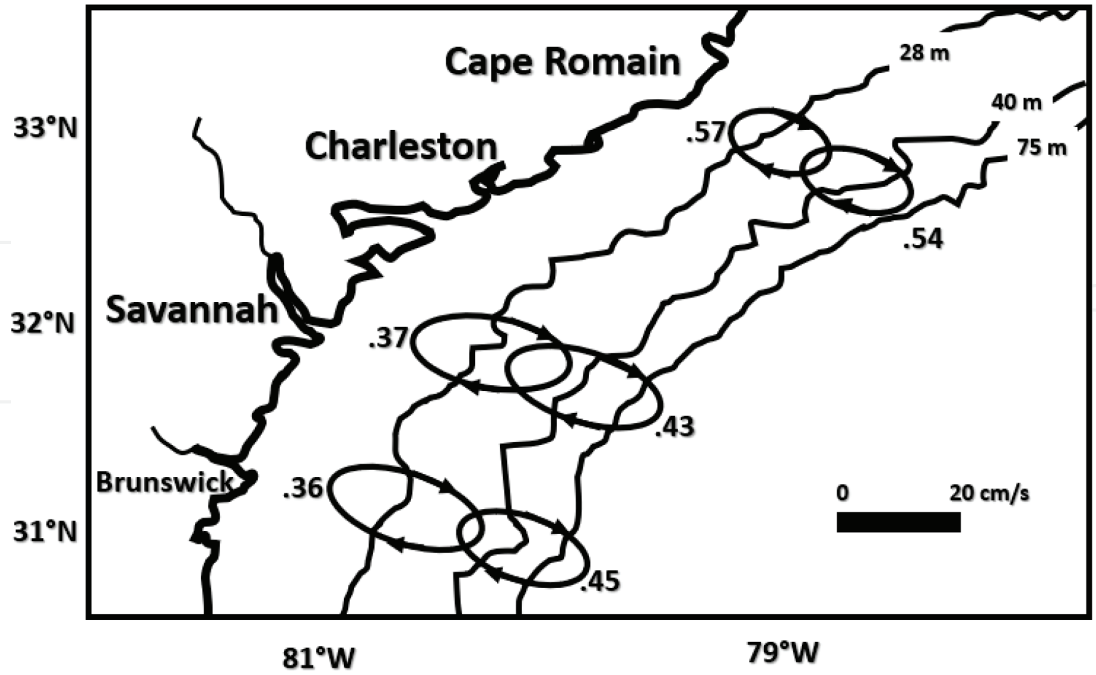
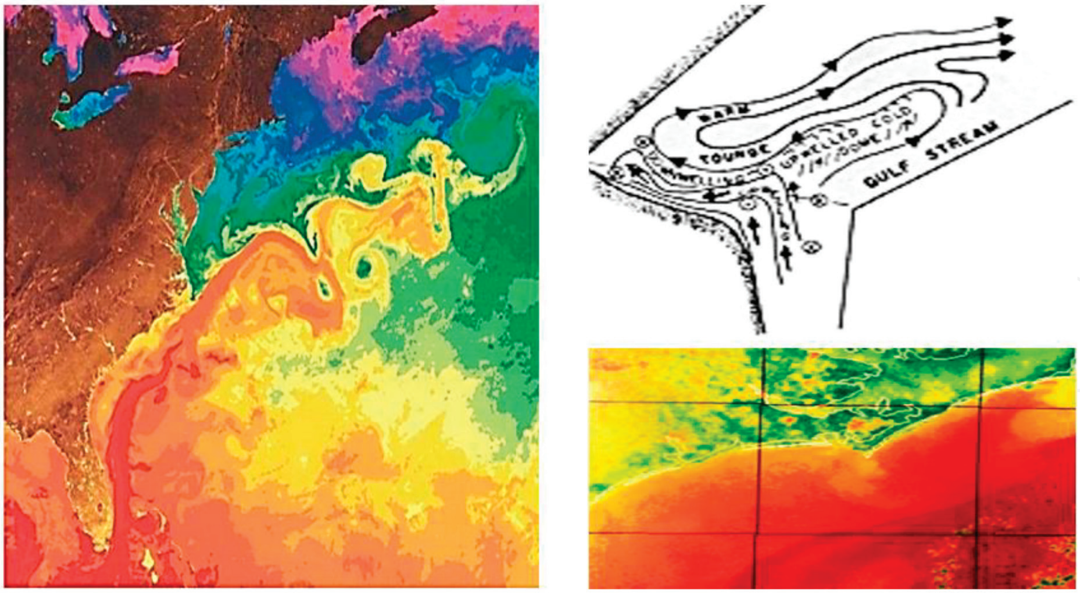


Figure 3.
Water particle motions due to the M2 astronomical tides along the 28 m and 40 m isobaths off Georgia, South Carolina, and North Carolina. The calculations of the clockwise rotating water parcels are computed directly from Eulerian current meter observations [5]. The numbers on the ellipses indicate the ratios of the onshore/offshore ellipse axes to the alongshore axes. The ellipse axes are about 2 km onshore/offshore and 1 km alongshore.

result would be that every 12 hours and 25 minutes, a parcel of water would end back up where it started. These observed water particle motions are visualized in **Figure 3**. Therefore, the astronomical tide is discounted as having been the agent responsible for moving the dinoflagellates across the shelf. We next consider Gulf Stream variability and features.

4. Gulf stream variability and frontal filaments

In a Sea Surface Temperature (SST) NOAA GOES satellite-based study, Pietrafesa [6] reported that the Gulf Stream Current deflects offshore near 31°N, 79°W, meanders laterally thereafter, and its lateral meander variability decreases downstream of this deflection. The seaward deflection of the Gulf Stream Current was determined to be caused by the presence of a topographic irregularity, which became known as the "Charleston Bump," actually Hoyt's Hill in the geological history of the region. The study conjectured that the topographic feature changed the vertical vorticity of the Gulf Stream by shrinking the vertical water column such that the Gulf Stream had to move offshore to deeper water to preserve its angular momentum balance. After the Gulf Stream moves into deeper water, given angular momenta requirements, it reroutes itself toward the coast. The process was speculated to affect the generation of Topographic Rossby Waves (TRWs) in that locale by Rooney et al. [7] and Pietrafesa and Janowitz [3]. These waves were found to propagate to the north along the shelf breaks of SC and NC [3, 8, 9], with periods between 2 and 12 days and propagation speeds of 30–40 km/d. The study of Sun and Pietrafesa [9] also discovered that the Gulf Stream Front has an inherent 8-day baroclinic instability that is a persistent source of downstream propagating waves. John and Schott [10] staged an Eulerian



(a)

(b)

Figure 4.
(a) Left panel depicts the Gulf Stream and its configurations in the North Atlantic Ocean basin; (b) right panel shows a Gulf Stream frontal filament in a NOAA SST mage and its conceptual flow field.

current meter study on the FL outer shelf and determined that the Gulf Stream meandered laterally, and they concluded that these onshore-offshore motions were northward propagating waves, with dominant wavelengths of 340 km and 170 km, periods of 12 days and 5 days, and propagation speeds of 28 km/d and 36 km/d, respectively. A NOAA GOES SST image is shown in **Figure 4a**, which shows Gulf Stream variability along the Atlantic Seaboard. We note the offshore deflection off Charleston and a variety of frontal features. The horizontal crests of these laterally meandering waves can bring surface layer parcels of water onto the outer continental shelves of the coasts of NC and SC. Moreover, these waves can fold back at their crests.

Pietrafesa and Janowitz [11] and Pietrafesa [12] evaluated Eulerian current meter data off NC and FL, respectively, and provided a detailed current meter–based spatial and temporal map of a TRW meander crest that folded back, which they referred to as a Frontal Filament, wrapped around an offshore cold core eddy (**Figure 4b**). In summary, meanders and the frontal filaments and the eddies they generate serve as the principal form of mesoscale variability along the path of the Gulf Stream Current, on the outer continental shelf within the South Atlantic Bight (between Cape Canaveral, FL, and Cape Hatteras, NC). From this suite of comprehensive studies, the Gulf Stream has been shown to display many degrees of freedom (**Figure 4a**). **Figure 4b** is a beautiful SST representation of a GSF. Warm Gulf Stream water traveling in the crest of a Meander folds back onto the outer shelf and then travels southwestward into and around the filament and then turns toward the northeast and back into the Gulf Stream Front. The Cartoon in **Figure 4b** shows that pictorially.

5. The 1987 Red Tide event as viewed in SSTs and numerical model output

In **Figure 5**, employing NOAA AVHRR-derived Sea Surface Temperature images (SST), courtesy of Dr. Steven Baig of NOAA's Atlantic & Oceanographic Laboratory

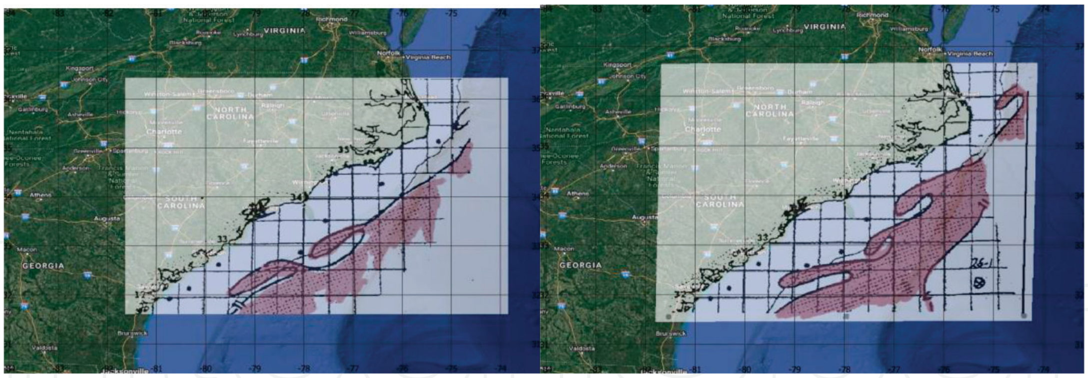


Figure 5.
NOAA AVHRR imagery of Gulf Stream waters with frontal filaments. (a) Left panel, October 05, 1987, image showing two filaments; (b) October 09, 1987, image showing three filaments. (SST images were provided by Dr. S. Baig, AOML). The magenta coloring is employed to depict the location of the Gulf Stream and its Frontal Filaments.

(AOML) that outlined the Gulf Stream and its frontal features, we see the presence of GSFs. At the time, these SST maps were a product that was hand drawn by Dr. Baig of AOML as a public service particularly the fishing industry. In the upper panel, two GSFs are shown to have been located between 32° and 33.5° on October 05. In the **Figure 5** lower panel, a third GSF has appeared and the three frontal features are between 32.25° and 34.25°. The southernmost GSF in **Figure 5** upper panel moved to Onslow Bay offshore waters as shown in **Figure 5** lower panel. An additional GSF had by then formed east of Cape Romain, SC. For the GSF located offshore of Onslow Bay to have propagated there from its previous location offshore of Charleston, SC, 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. We will test this with our numerical model scenario present below.

From the above data-based hypothesized description, Red Tide dinoflagellates could have been loaded into the Loop Current in the Gulf of Mexico offshore of Naples, Fla., and eventually could have been positioned in a large Gulf Stream Frontal Filament (GSF) offshore of Onslow Bay on Oct. 09. If the dinoflagellates were located in surface layer waters of the GSF, then the obvious question occurs: How could the dinoflagellates have been transported out of the filament and across Onslow Bay, a distance of 90–110 km (56–68 mi.) by October 31 when the Red Tide was first observed on the NC 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 and Long Bays? We next employ a numerical atmospheric and ocean current model system to simulate the events of 1987.

In our numerical model simulation, we employ two different reconstructed wind fields, so as not to appear to bias the atmospheric driving force. On the oceanic side, we employ the Regional Ocean Model System (ROMS) ocean circulation model [13]. **Figure 6** depicts the seeding of coastal waters on the West FL shelf with Red Tide plants that are assumed passive tracers. Two model simulations were conducted to offer comparisons. One simulation employed the North American Regional Reconstruction (NARR) winds (https://www.emc.ncep.noaa.gov›mmb›rreanl›index.

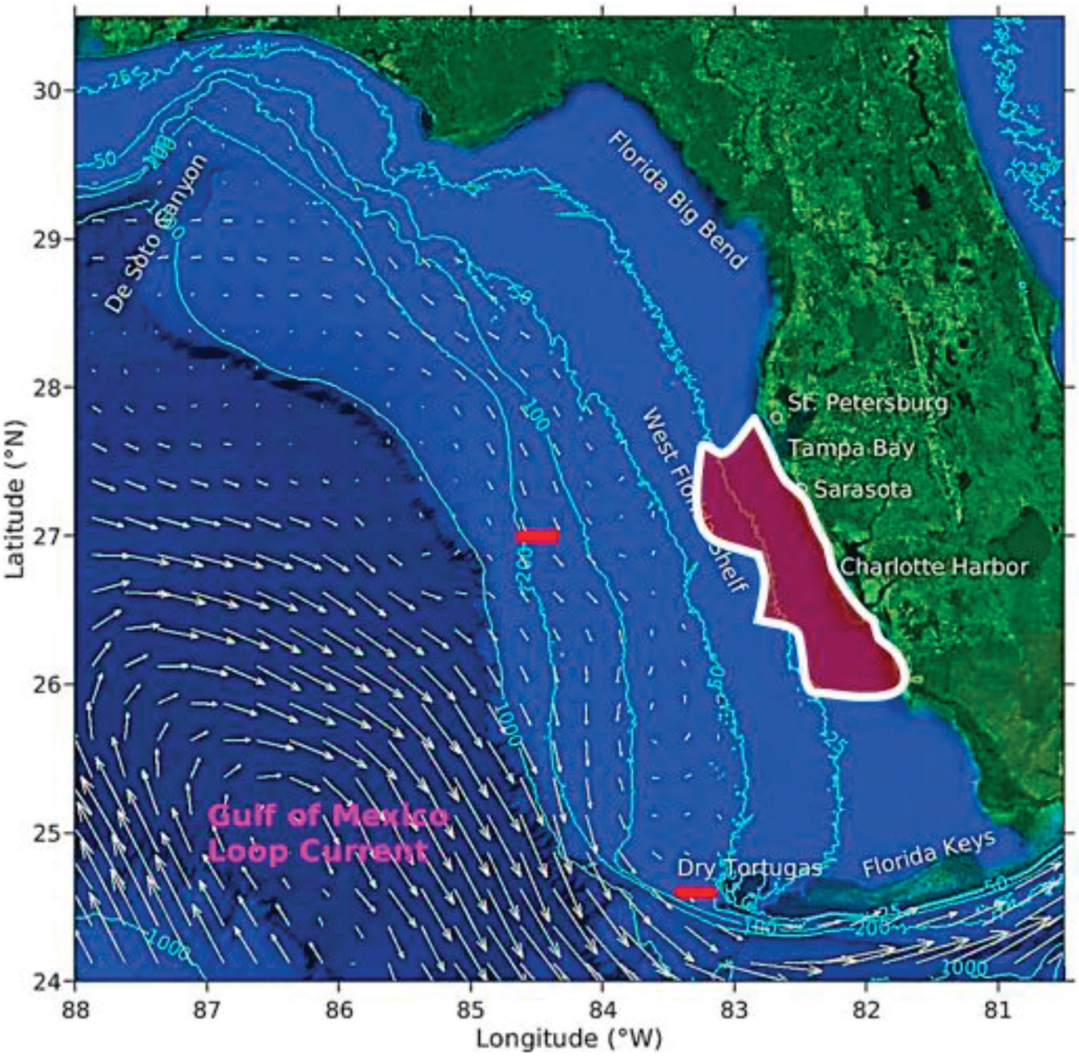


Figure 6.
Patch of red tide cells dumped into the ROMS Ocean current model in the surface waters of the west coast of FL on August 24, 1987, with a triple-nesting approach in the ROMS Ocean currents model.

html) and the second, the European Centre for Medium-Range Weather Forecasts (ECMWF) winds (https://www.ecmwf.int).

Figure 7 presents the NARR wind fields used in the model experiment, by way of example. As the winds on the west FL shelf were consistent from late August to early September, we present that sequence. In **Figure 8**, the numerical model simulations employing the NARR winds versus the ECMWF winds (which are not shown) are presented. They are quite comparable, providing credence to our mechanical wind-forcing hypothesis.

In the numerical model experiments, two conclusions are reached: (1) the atmospheric winds in late August and early September 1987 on the West Florida Shelf were sufficient to transport the Karina Breve cells from the west coast of Florida to the Loop Current to the Florida Current—and into Gulf Stream system; (2) the combination of the wind effects, from Cold Fronts in the GOM and ETCs; on the other hand, the effect of the Gulf Stream meanders and frontal filaments are necessary to transport the passive tracer from the Gulf Stream to the inshore area of the NC and SC coasts. We next consider the atmospheric wind fields along the southeastern Atlantic Seaboard in the fall 1987.

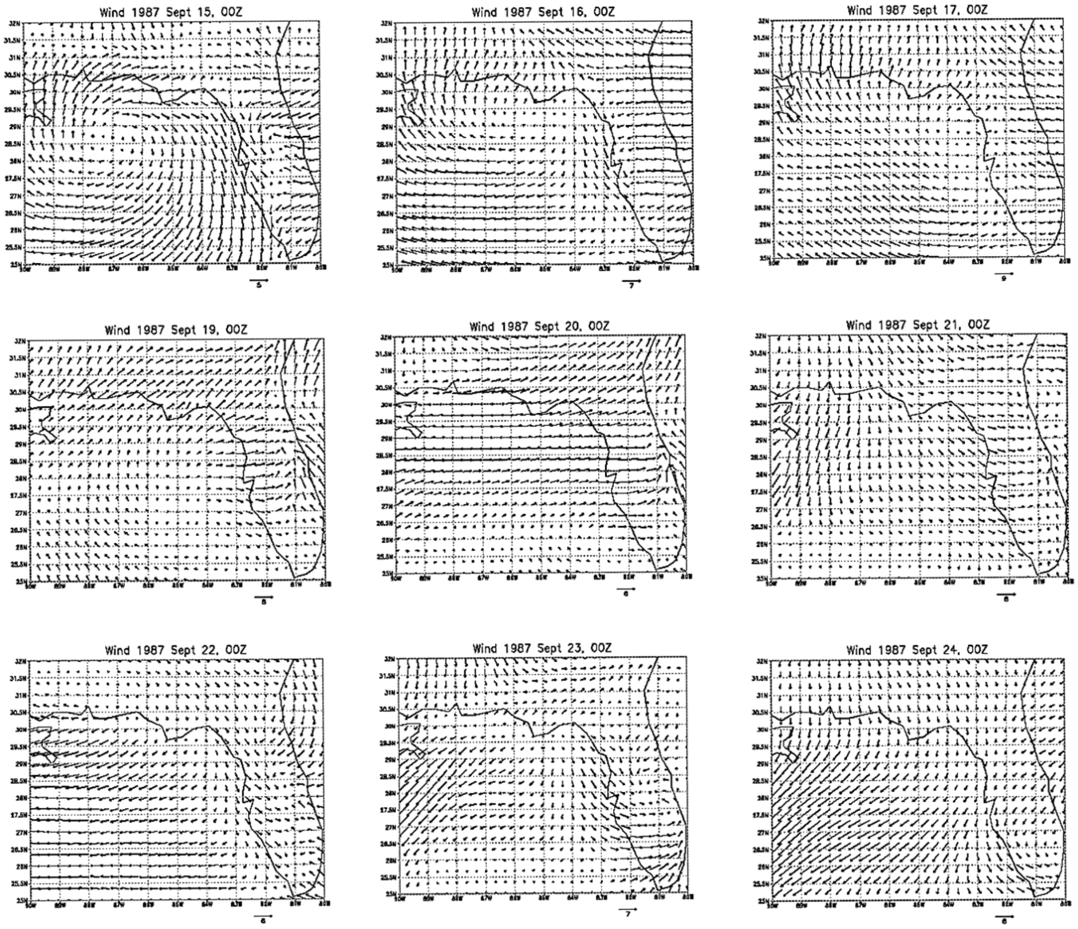


Figure 7.
NARR-based wind fields over the west coast of FL on August 24 1987, during the numerical passive tracer experiment.

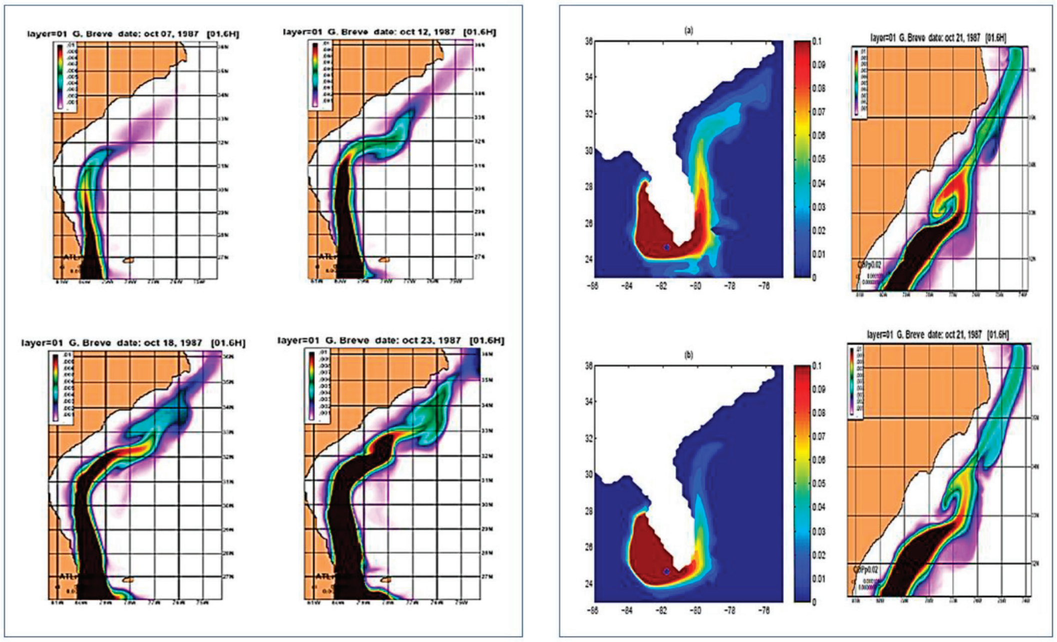


Figure 8.
The passive tracer wind-driven numerical model experiments employing the NARR versus the ECMWF driving fields, both driving the ROMS Ocean currents model. (a) Left panel, the passive K-breve algae; (b) right panel, a surface oil spill in the GOM being transported to the southeastern Atlantic seaboard.

6. The atmospheric wind field and extra-tropical cyclones

The wind field as observed by the National Weather Service (NWS) at the Cape Hatteras Lighthouse station (not shown) was evaluated over the period September 1 through December 31, 1987. The wind's velocity vector, i.e., wind speed and direction, is measured and recorded every 3 hours. The Cape Hatteras wind vector time series data were chosen since no meteorological buoy data were available (from the region) for the Fall of 1987. The Hatteras winds were deemed more representative of outer shelf Onslow Bay wind conditions than were winds from Wilmington or Beaufort, NC. Weisberg and Pietrafesa [14] 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 2.5–6.5 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 from the mainland and are thus deemed more representative of actual over-the-water winds. It is of note that the region surrounding Cape Hatteras is a spawning region for wintertime atmospheric low-pressure systems or cyclonic storms [15].

During the late fall, winter, and early spring period, Atlantic low pressure systems known variously as Nor'easters, Atlantic Lows, Cape Hatteras Lows, and Extra-Tropical Cyclones (ETCs) are omnipresent over the coastal zone principally from South Carolina (SC) to Virginia (VA) [15] but actually extend from 25° N latitude to 75° N. ETCs intensify, and often form, throughout this zone, centered about Cape Hatteras [15]. The ETCs can deepen, i.e., further intensify, or spawn through a process known as "cyclogenesis" [16] and develop rapidly along and off the coast. The SC to VA coastal region is unique in its position adjacent to the warm waters of the Gulf Stream. Its alignment is favorable to the generation of offshore flow in response to winds typically associated with the incursion of cold, dry air from the north and west, often referred to as cold-air outbreaks (CAOs). The oceanographic setting in the region between SC and VA is such that the Gulf Stream Front (GSF) is omnipresent along the shelf-break between 32.5° and 35.5° N. During occasions of incursions of cold dry air streaming into the area from the north, local air temperatures can drop to between 0°C and 10°C, hence a CAO and the formation or genesis of an ETC. Cione et al. [15] determined that the mean path of the ETCs was from the SW to the NE and located about 30–50 km offshore so that the winds on the coastward side of the storm were from the NE to SW. As it occurs, the wind field present on the NC/SC coasts (**Figure 9**) was created by the passages of a series of ETCs.

The ETC winds would have driven offshore waters shoreward as depicted in **Figure 10** (from [3]). The basic dynamic balance relating the onshore-offshore component of the flow field in the surface layer of the water column is described by invoking conventional Ekman theory, in which the onshore-offshore (diabathic) mass flux, Mx, in the surface layer, D, is related to the alongshore (parabathic) component, Wy, of the total wind-stress vector or as expressed via: $Mx = Wy/fD$ (1), where: Mx = Vertical Integral of $r(udz)$ from 0 to D, the water surface to the depth D, the depth of the surface Ekman Layer, r is the water density, u is the diabathic or cross shelf water velocity, 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.

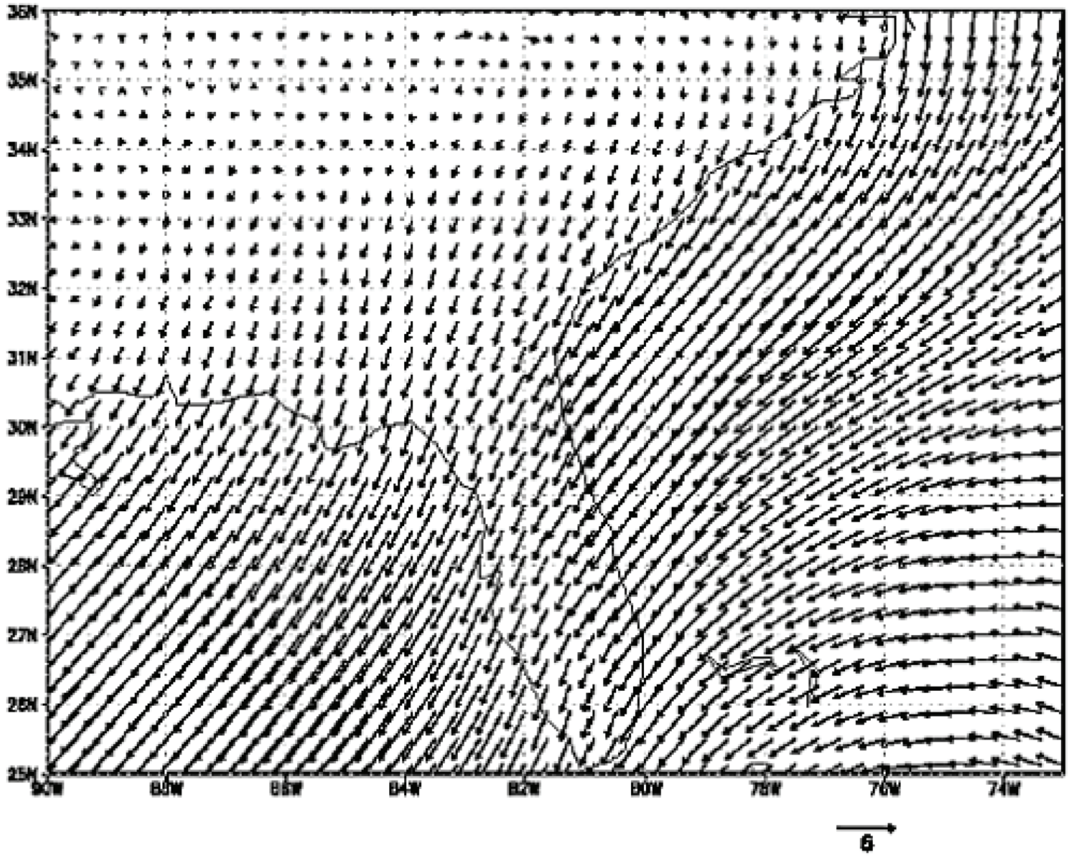


Figure 9.
The mean winds for the month of October 1987 from NARR winds (https://www.emc.ncep.noaa.gov›mmb›rreanl›index.html).

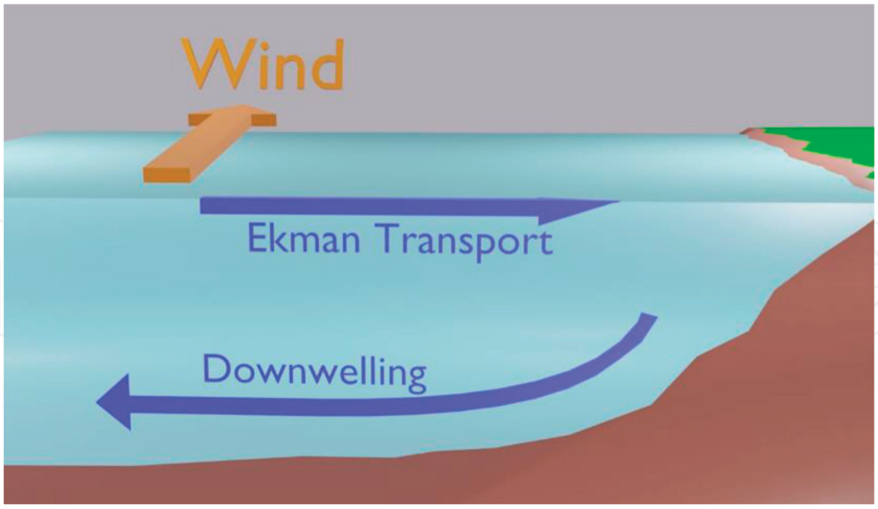


Figure 10.
Wind blowing with the coast to the right, creating a surface Ekman transport toward the NC and SC coasts.

The surface layer shown in **Figure 10** cartoon will be of the order of 5–25 m thick as a function of wind speed, vertical density gradient, and vertical velocity gradient on the NC and SC shelfs. Thus, a positive Wy (a northeastward wind, not shown) yields a positive Mx (surface layer transport to the southeast or offshore) and a negative Wy (a southwestward wind, as shown) yields a negative Mx (surface layer transport to the northwest or onshore). From October 9 through November 9, the wind velocity vector at Cape Hatteras was directed toward the southwest to south sector with essentially no reversals. From October 12 to 18, the winds were especially strong toward the south-southwest. On November 8th, the winds switched to become northeastward to northward. Over the entire 19-day period, October 9–27, the mean Wy, alongshore wind-stress component, was about 0.75 dynes/cm^2, which suggests a surface Ekman layer, D, of approximately 12–15 m thick and a vertically averaged onshore Ekman layer speed of approximately 6.3 cm/sec (or 5.5 km/day).

During the October 9–27 period, the distance water parcels and/or passive drifters would have moved across the shelf in the surface layer, which is about 105 km (65 mi). To calculate the total trajectory of a water parcel located in the surface layer requires that we integrate the vertically averaged (mean) onshore velocity component over the total time, with the wind fluctuating but remaining favorable for a shoreward moving surface water layer. For example, from October 13 to 16, the wind blew toward the SSW with an effective stress of between 1 and 3 dynes/cm^2, causing an onshore displacement of the surface layer of some 52 km (32 mi), about 13 km/day. By October 19, the surface layer had moved an additional 16 km (10 mi) shoreward driven by the SW winds of 0.3–0.5 dynes/cm^2. At this point, a passively drifting, buoyant particle imbedded in the GSF prior to October 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 October 19.

In **Figure 11**, the NOAA AVHRR SST map created by Dr. S. Baig (AOML) is shown. It appears that the entire Gulf Stream Front system of three filaments, which were present on October 9 (**Figure 5** lower panel), were subsequently mechanically driven

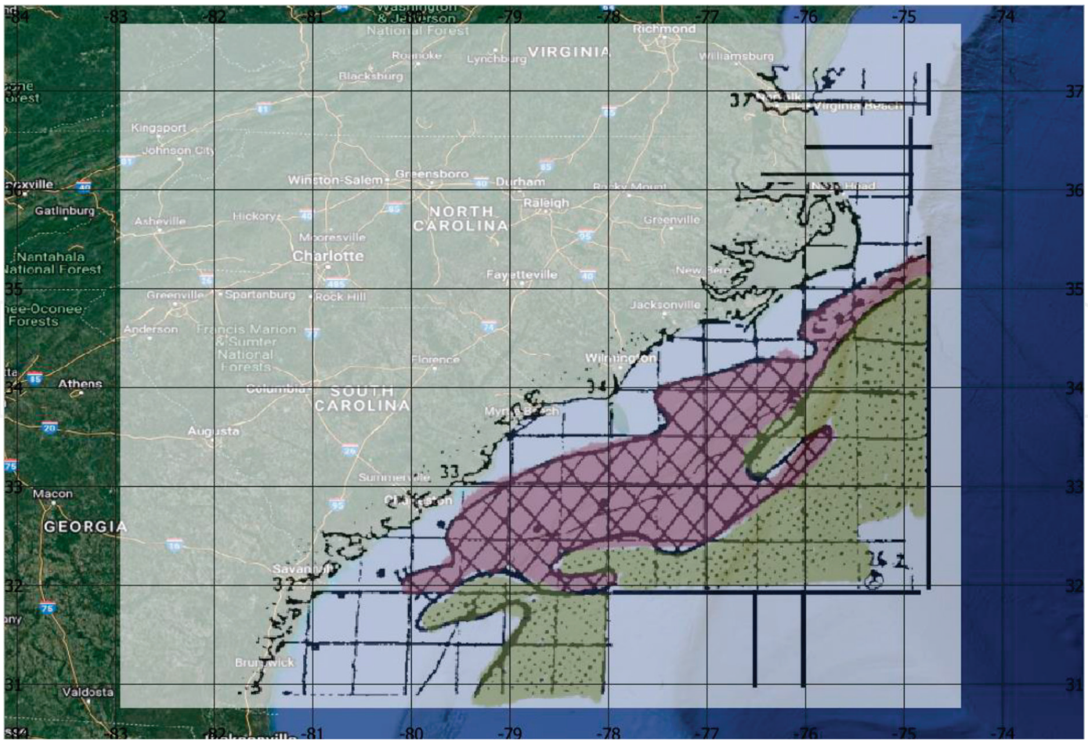


Figure 11.
NOAA AVHRR image of the Gulf Stream and GSF on October 19 1987 (courtesy of Dr. S. Baig, AOML). The magenta coloring is employed to depict the Gulf Stream surface waters that have been mechanically driven by the atmospheric winds towards the coasts of the Carolinas. The green coloring is employed to depict the Gulf Stream and its Frontal Filaments.

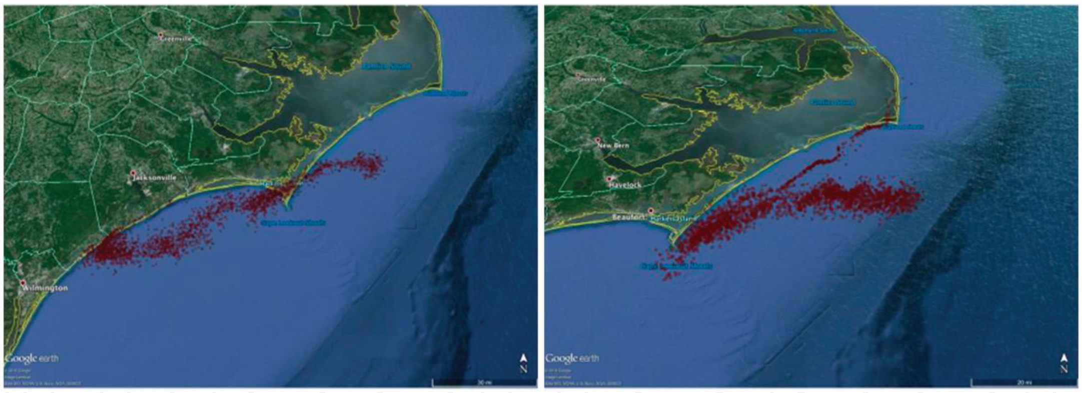


Figure 12.
The numerically modeled trajectory of surface oil spills in central Raleigh Bay NC: (a) left panel, shows the surface trajectory of a virtual oil spill driven by an ETC from the middle of the northern bay to the southwest into the lower bay; (b) right panel, shows the surface trajectory of a virtual oil spill offshore and then entrained into a passing GSF. Both wind driven (a) and ocean feature (b) events, project oil being carried to the NC coast. The Red Dots are employed in both panels to depict the trajectories of the oil spilled offshore and carried via surface currents.

or rather, advected, onshore. The thermal frontal feature located in midshelf waters suggests that frontal waters, which 10 days previous were part of three filaments, now blanket the mid to outer shelf of Raleigh and Onslow Bay NC and Long Bay NC/SC. Amazingly, the warm-water front appears to have maintained its general outline, essentially intact, from 10 days earlier. From a comparison of **Figure 5** (lower panel) and 10, it is clear that the warm water boundary defining the filament front has moved more than 70 km across the shelf.

From October 17 to 27, the surface layer was 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 NC. By October 31, the entire Onslow Bay coastline could have been invaded by filament waters. Then, from October 31 to November 7, the southwestward winds would have blown an additional water mass 18 km wide in the onshore/offshore direction and 13 m thick toward the coast. In all, a block of water 100 km wide in the longshore direction, 13 m thick in the vertical, and 163 km wide in the cross-shelf direction moved across Onslow Bay coastal waters over the 30-day period. This is depicted in **Figure 11** as the rosette-colored water masses. So, every day, on the average, a block of water 40 feet thick, 62 miles long, and 3.3 miles wide was advected toward the coast. At least 12 of those blocks reached the NC and SC beaches. That scenario, depicted inferentially by winds and SST images, raises the question: Could this scenario be numerically modeled to validate the data-based explanation of the physical dynamics? We address that next.

An additional numerical model experiment, employing the National Weather Service Weather Research Forecast Model (WRF), described in Skamarock et al. [17] and ROMS. If oil were to be drilled in NC waters, and an oil spill occurred between September and March, when the winds are predominately out of the North to East Quadrant (Weisberg and Pietrafesa, 1983), then the oil would likely reach NC coast as shown in **Figure 12a**. If the winds were absent, but a GSF was passing by (e.g., **Figure 4b**), particularly where these filaments nearly hit the Outer Banks near Cape Hatteras NC, then the oil spill would be carried as shown in **Figure 12b**. SC has a ban on oil drilling, so it was not considered in the latter two experiments.

7. Conclusions and summary

Oil Spills have never occurred on the North Carolina or South Carolina US continental margins. However, they have occurred in the Gulf of Mexico where a great many oil drilling platforms are located, and many oil tankers transit Gulf Waters daily. In 2010, there was a major oil spill in the Gulf. In 2017, the US administration lifted a ban on oil drilling in North Carolina Coastal waters. So two questions arise: One, could an oil spill in the Gulf reach Carolina coastal waters? Secondly, if an oil spill were to occur in the future off North Carolina, could it reach the beaches under typical environmental conditions? We address both questions.

To address non-local oil spills reaching the Carolinas, we revisit a Red Tide outbreak on the West Florida Shelf that reached the coasts of the Carolinas. In August 1987, a Red Tide occurred on the West Florida continental shelf off Naples, Florida. Those deleterious plants reached North and South Carolina shelf waters by late October. Using data from that era, we create a data-based scenario by which atmospheric conditions combined with oceanic currents carried the Red Tide plants over 1600 kilometers (1010 miles). Then based on the surrogate Red Tide plants, we numerically modeled the atmospheric and oceanic conditions of 1987 and dumped passive oil particles into the numerical model off Naples, Florida. The model predicted that the oil would have reached Carolinas coastal waters. Thus, we demonstrate from both data and numerical modeling that oil spills in the Gulf of Mexico have the potential to reach the US eastern seaboard via a combination of atmospheric storms, major ocean currents, and atmospheric wind-driven surface currents.

To address the possibility of a local oil spill reaching the beaches of the Carolinas, we consider the 2017 U.S. White House removal of an oil-drilling ban in North Carolina coastal waters. Herein, we released oil spilled in a projected oil drilling location on the North Carolina shelf into our atmospheric and oceanic numerical model. Again, given typical atmospheric and oceanic phenomena, the hypothetically spilled oil reached the beaches of North Carolina.

Thus, we have demonstrated that as a matter of a series of non-local and local atmospheric and oceanic phenomenological consequences, in outer continental shelf waters, oil in the upper 15 meters of the water column can be carried long distances and then driven toward the coast and reach the beaches. This is especially true during the passage of an atmospheric Extra-Tropical Cyclone. If a Gulf Stream Frontal Filament is present offshore, then during the passage of a cyclone event, oil in the upper 15 meters, even well offshore (~75 m deep) will be carried to the coast.

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