

INTEGRATION OF PHYSICAL OCEANOGRAPHY
WITH SPATIO-TEMPORAL PATTERNS
OF STRANDED SEA TURTLES IN NORTH CAROLINA

by

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Abstract

The conservation status of sea turtles warrants research on their mortality rates (Turtle Expert Working Group 1998). Stranded carcasses document mortality but represent an unknown fraction of total number of dead turtles at-sea (Murphy and Hopkins-Murphy 1989, Epperly et al. 1996). In addition to water temperature, tidal forcing, decomposition rates, scavenging rates, and the spatio-temporal distributions of turtles and mortality sources, wind and water current regimes probably play a major role in the stranding of carcasses on beaches. Fifteen years of hourly wind speed data, recorded off the North Carolina coast, were transformed into vectors, converted into wind stress magnitude and direction values, and averaged by month. Near-shore surface currents were then modeled for the South Atlantic Bight via a three-dimensional physical oceanographic model (Werner et al. 1999). Estimated currents and particle tracks were compared to the spatial locations of sea turtle carcasses stranded along ocean-facing beaches of North Carolina. The seasonal development of along-shelf flow coincided with increased numbers of recorded strandings in late spring and early summer. The model also predicted net offshore flow of surface waters during winter, typically the season with the fewest relative strandings. Modeled lagrangian drogues were retained in shallow ($\leq 20\text{m}$) bathymetric contours, indicating that turtles killed only very close to the shore may be most likely to strand. During seasons when net along-shelf flow was present, turtles were likely to have died "upstream" from the residual current. A reevaluation of oceanic drift bottle experiments may also provide a reasonable upper bound to describe how far carcasses could theoretically travel and how likely those carcasses could make landfall from points offshore. Though qualitative, this research a.) provides a starting point for more robust analyses and b.) demonstrates that stranding research requires an understanding of ocean physics in addition to sources of mortality.

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Introduction

Occasionally, sea turtle carcasses drift so close to shore that they become stranded in shallow water or on beaches. The majority of strandings involve individuals that died at-sea due to natural or anthropogenic causes. Because the number of recorded sea turtle strandings represents a minimum estimate of mortality (Murphy and Hopkins-Murphy 1989, Epperly et al. 1996), and in light of the conservation status of turtle species, recent management guidelines have strongly recommended an investigation of landfall patterns of stranded turtles (Turtle Expert Working Group 1998). Research on marine turtle strandings, however, has proved challenging because most stranded carcasses are decomposed and offer little direct evidence of cause of death (Sis and Landry 1992, Turtle Expert Working Group 1998).

I. General stranding patterns

The evidence obtained from stranded turtles is strictly observational. Inferences made from data collected systematically in uncontrolled settings are limited, of course, for simple association does not imply causation. Nonetheless, patterns of marine turtle strandings throughout the South Atlantic Bight and, in particular, coastal North Carolina may reveal much about the physical locations of mortality and the probability of stranding as a function of spatial location.

i. Turtle species

The most common species to strand on ocean-facing beaches in North Carolina from 1997-1999 were the Loggerhead (*Caretta caretta*) and Kemp's ridley (*Lepidochelys kempii*) (R. Boettcher, personal communication). Among the five marine turtle species

that are known to reside in or migrate through U.S. coastal waters, *C. caretta* and *L. kempii* are classified under the U.S. Endangered Species Act as a threatened species and an endangered species, respectively (NRC 1990).

Most remaining members of *L. kempii*, largely considered the Cheloniid species in the greatest danger of extinction, belong to a single nesting population (Pritchard 1997). Although this species' population experienced a significant increase in strandings in 1994 and 1995 in the southeastern U.S., annual nest numbers have increased during the 1990's (Turtle Expert Working Group 1998). Kemp's ridley turtles are most abundant in the Gulf of Mexico, feeding primarily in waters off Louisiana (Hildebrand 1979). Individuals that strand along the North Carolina coast are adult migrants or juveniles transported via Gulf Stream intrusions from the Florida Straits (Hildebrand 1979).

The northernmost extent of the nesting range of the Western North Atlantic *C. caretta* population includes North Carolina (Turtle Expert Working Group 1998). Loggerheads are consistently the most numerically dominant sea turtles to strand on North Carolina beaches (Epperly et al. 1996; R. Boettcher, personal communication). Large juveniles and small subadults (50-80 cm straight carapace length) were the most frequent lifestage classes found stranded on North Carolina beaches from 1981-83 (Crouse et al. 1987). By way of comparison, the mean SCL of adult loggerheads in the southeastern U.S. approaches 92 cm (NRC 1990).

ii. Spatio-temporal variation of strandings

Relative decreases in strandings during winter months have been observed in South Carolina, Georgia and Florida (Murphy and Hopkins-Murphy 1989). In North Carolina, from 1995 to 1999, the lowest number of recorded ocean-beach strandings of

both *C. caretta* and *L. kempii* occurred consistently from December through March (Figures 1-2 created from unpublished data provided by R. Boettcher). The rate of turtle strandings in North Carolina typically increases to the south of Cape Hatteras in the summer and in the immediate vicinity of Cape Hatteras in the winter, hypothetically due to the respective activities of shrimp and flounder trawl fisheries (NRC 1990).

II. Potential factors that influence stranding patterns

Ideally, attempts to investigate stranding patterns should account for factors that affect i.) the duration of carcass buoyancy, ii.) the probability of a carcass making landfall, iii.) the spatial and temporal distribution of turtles at-sea, and iv.) observer accuracy and consistency (see also Table 1).

i. initiation and duration of carcass buoyancy

Several interrelated factors could influence the finite amount of time that a particular carcass may spend afloat. These factors may include, but are not limited to, carcass size, variability in carcass scavenging, decomposition rates, air and sea surface temperature, and the physiological state of the turtle prior to death.

ii. carcass landfall probability

The probability of a particular carcass making landfall is also influenced by several factors, including the direction, intensity and seasonality of prevailing winds, surface and near-bottom current regimes, M2 or lunar tidal effects, and the spatial proximity of mortality source to shore (Murphy and Hopkins-Murphy 1989, NRC 1990, Crowder et al. 1995, Epperly et al. 1996). Oceanic conditions that produce nearshore currents could facilitate the stranding of drifting turtle carcasses (Crowder et al. 1995),

and hence partially explain the increased number of strandings observed during certain seasons in the southwestern Atlantic (e.g., spring; Amos 1989). Likewise, winter wind regimes may initiate net offshore flow in shelf waters, thus precluding carcass landfall (Epperly et al. 1995).

iii. spatio-temporal distribution of turtles

The presence and distribution of sea turtles prior to mortality will undoubtedly affect the relative numbers and species diversity observed in the subset of carcasses that strand on shore. Possessing preferences for diet and thermal conditions, sea turtles are capable of actively moving into preferred habitats or avoiding less than optimal habitats (Coles and Musick 2000). Surveys of recreational fishers in North Carolina revealed seasonal peaks of sea turtle abundance in the western Atlantic, including a peak from May to June (Epperly et al. 1995). Aerial pelagic surveys documented that sea turtles are typically observed in waters shallower than 50 meters, are rarely seen seaward of the Continental Shelf, and are observed at distances farther offshore during fall and winter months (Murphy and Hopkins-Murphy 1989, NRC 1990, Epperly et al. 1995). Other aerial surveys, anecdotal sightings and incidental take data via commercial fishers have shown that sea turtles are relatively more abundant near convergence zones (Lutcavage et al. 1997), close to the western boundary of Gulf Stream (Hoffman and Fritts 1982), and along the shelf break or 200 m isobath of the Mid Atlantic Bight (Lutcavage et al. 1997). An absence of sea turtles in coastal waters may result in fewer strandings recorded in winter (NRC 1990), but the absence of stranded carcasses may or may not indicate the presence of turtle mortality.

iv. observer accuracy and consistency

Not all turtles that strand may be reported. Likewise, reporting coverage may vary over time and space. Some reported carcasses may be inaccurately identified to species due to the degree of decomposition. Some observers may have more experience with stranding protocol than others. Observer error may also occur later during data transcription from field notes to computer. A decrease in observer coverage in local vicinities could also explain the phenomenon of lower strandings during winter months (NRC 1990).

III. Research Objectives

I am interested in investigating three questions related to ocean-beach strandings of sea turtles in North Carolina:

1. What is the relationship, if any, between near-shore current fields and observed stranding patterns?
2. In light of seasonal current regimes, can known stranding locations be used indirectly to identify or to rule out mortality sources at-sea?
3. Can a reevaluation of oceanic drift bottle experiments help to determine stranding likelihood for floating objects?

Although coastal water circulation tends to be local and hence difficult to predict, due primarily to shoreline geography and topography (S. Lozier, personal communication), recent advances in coastal current modeling have been made. Using a physical oceanographic model (Werner et al. 1999) to predict near-shore surface water regimes inside the South Atlantic Bight (SAB), I compared real-world turtle stranding patterns to modeled currents. Associations derived from the model could begin to clarify the

relationship between at-sea turtle mortality and on-shore turtle strandings. This type of information is currently unavailable to wildlife managers.

Methods

I. Wind data acquisition and conversion

Historical wind data were downloaded from the National Data Buoy Center website (<http://www.ndbc.noaa.gov>). Wind speed magnitude (m/sec) and direction (degrees clockwise from North) were recorded hourly via anemometer at a C-MAN (Coastal-Marine Automated Network) station at the Diamond Shoals Navigation Light (DSL7), located at 35.15 N, -75.30 W off Cape Hatteras, NC. Winds were subsequently transformed into vector format, and each wind's vector was then resolved into its corresponding u (easterly) and v (northerly) components by the following equations:

$$\text{Easterly component} = ws * \sin [(wd + 180) * (\pi/180)]$$

$$\text{Northerly component} = ws * \cos [(wd + 180) * (\pi/180)]$$

where ws = wind speed (m/s)

wd = wind direction (degrees clockwise from North)

This transformation was necessary for three reasons:

- 1.) Designed to point into the wind (i.e., towards the direction in which the stress is applied), anemometers record winds as blowing from direction x . Adding 180 to the given wind direction converted wind direction from "direction blowing from" to "direction blowing to". The convention for expressing direction differs between scientific disciplines, the former representing the meteorological expression while

the latter is the common oceanographic expression. This practice is easily confusing. The suffix “-erly” denotes meteorological direction while the suffixes “-ern” or “-ward” refer to the oceanographic form. For example, easterly winds blow from the east while eastward currents flow to the east. For consistency, I will report wind and current direction using both expressions: oceanographic form followed by meteorological form in parentheses.

- 2.) Data were manipulated within spreadsheet programs on a PC. The spreadsheet’s trigonometric function expected arguments in radians rather than degrees, hence the need to multiply the formula by pi/180.
- 3.) The flow field model required input in the form of vector components.

Southerly and westerly winds were simply recorded as negative values of their respective opposing directions. The u and v vector components were determined and averaged for each month over fifteen years (1985-99). The magnitudes of each component, originally recorded as velocities (m/s), were ultimately transformed into forces (Pascals). Since speed and stress have a non-linear relationship, a specialized Matlab script was used to facilitate the transformation (Blanton et al. 1985). The resulting easterly and northerly wind stress components were converted from Pascals into Dynes/cm², where 1 Pascal equals 10 Dynes/cm².

The stress magnitude (r) was calculated via vector addition of the u and v directional components by means of the Pythagorean Theorem:

$$u^2 + v^2 = r^2$$

$$\text{sqrt} [(u^2) + (v^2)] = r$$

Similarly, by taking the arctangent of v/u , wind stress direction (θ) was determined. Multiplying the resulting output by $180/\pi$ converts the theta value from radians to degrees CCW from True East.

II. The physical oceanographic model

The underlying structure of the oceanographic model (Werner et al. 1999) is a finite element matrix. The matrix is composed of 3335 nodes that are interconnected by 6416 elements, forming a triangular irregular network or tin (Figure 3). The spatial domain of the matrix incorporates the continental shelf and slope of the Mid- and South-Atlantic Bights (Figure 4). I focused exclusively on the model domain in proximity to North Carolina, part of the northern SAB. Inter-node distances are approximately 1 km for coastal North Carolina. Twenty-kilometer distances separate most offshore nodes. The matrix serves as the domain for two computer models: a flow field model (that estimates water current patterns) and a particle tracking model (that estimates the lagrangian motion of drogue floaters).

i. Flow field model

Wind stress magnitude and direction values served as input for the flow field model. Each node in the matrix has a specific response to a wind stress. Node responses to winds, recorded as easterly and northerly water current components, indicated the hypothetical flow field of the water body. After obtaining the model's output for True North (0°) and True East (90°) winds (B. Blanton, personal communication), it was possible to use these directions to approximate the model's response for any given wind

direction, without having to run the model separately for each different wind direction.

Time constraints prevented me from driving the model by the M2 tidal response.

The flow field model makes several important assumptions:

a.) The model does not account for Gulf Stream effects, which demonstrate weekly and seasonal variation (Schumacher 1974). The Gulf Stream represented the dominant flow source beyond the 40m isobath inside the SAB (Werner et al. 1999). Inner shelf regions (i.e., areas landward of the 40m depth contour), therefore, may be subject to less frequent incursions by the Gulf Stream relative to the outer shelf (Werner et al. 1999). Although this does not eliminate the bias surrounding the model's exclusion of Gulf Stream effects, it should reduce the magnitude of the bias. Intrusions of the Gulf Stream (e.g., filaments, anticyclonic warm core rings) could enhance the number of offshore carcasses transported to the nearshore zone. Conversely, carcasses in nearshore waters may also be carried offshore by the same phenomena.

b.) The model was configured to produce surface water response to wind stress. I assumed that most carcasses, while buoyant, would remain in the upper portion of the water column and would hence be most influenced by surface currents.

Sis and Landry (1992) designed an elegant field experiment to document the post-mortem changes of *Pseudemys scripta elegans* (red-eared pond slider), a freshwater turtle species, in an estuarine lagoon. Thirty-four of 36 euthanized turtles sank immediately upon placement in water shortly after death. Autolysis (e.g., destruction of cells via their own enzymes) of organs and tissues was observed between 8 and 16 hours post-mortem. All individual carcasses surfaced between 16 and 32 hours after the project's commencement. Assuming that recently killed sea turtles behave in a similar fashion,

bottom currents would only affect carcasses during the first 24 hours after death. Trial runs of the model consistently predicted smaller magnitudes of bottom transport relative to those of the surface, due to the loss of energy by friction as one travels down the water column. Despite differences in flow direction, modeled particles at depth were transported over relatively short distances. So, it is hypothesized that recently submerged carcasses would be subjected to less stress relative to the surface and, hence, would not move far before achieving buoyancy.

The comparison of freshwater turtles to marine turtles, though biased by the species' size and physiological differences, provides some insight into how sea turtle carcasses could generally behave. In preliminary studies, differences in body mass were not found to significantly influence terrestrial decay rates of human cadavers (Mann et al. 1990). It is unknown how sea turtle carcasses specifically behave in the water column. However, because the specific gravity of sub-adult and mature sea turtles is greater than that of seawater (Milsom 1975), it is reasonable to assume that, shortly after death, a sea turtle's body will initially sink (Epperly et al. 1996). As decomposition proceeds, internal microbial activity eventually produces an adequate amount of gas to achieve carcass buoyancy (Crowder et al. 1995). A deceased turtle, however, will only float for a finite period of time. If the body, uncompromised by scavengers, has not yet reached the shore within this period, it will sink, not to rise again (Epperly et al. 1996). This means that any stranded turtle recorded on shore must have been afloat for a discrete time period, passively influenced by currents. It is largely unknown just how far drifting carcasses may travel, regardless of their relative positions within the water column. Furthermore, a proportion of the carcasses that could possibly achieve landfall (due to favorable winds

and current regimes, having died spatially close to shore) may be scavenged to such an extent as to make it impossible for them to maintain integration or sustain buoyancy (Crowder et al. 1995).

c.) The model response is domain-wide and assumes steady-state conditions. Uniform wind fields, however, generally do not occur in natural settings (Schumacher 1974). Because I am seeking to explain large-scale seasonal patterns, rather than particular events, this assumption is not a serious issue.

d.) The model relies on wind data retrieved from a single station. Werner et al. (1999) argued that the central location of DSNL C-Man station within the model domain provided data that best estimated the conditions experienced throughout the MAB and SAB. Nevertheless, the study area is vast, making the dependence on one station potentially subject to local extremes or other biases. Empirical evidence from past studies in the South Atlantic Bight, however, indicate that my findings agree with seasonal wind patterns (see Discussion).

e.) The model relies on monthly averaged wind data. Obviously, variability in wind speed and direction can be very high over the course of the year. The months of April, May, August and September typically have the highest wind variation during the year in the SAB (Blanton, personal communication). This is due in part to the biannual movement of the Bermuda-Azores high pressure system and to the seasonal occurrence of hurricanes (Blanton, personal communication).

Furthermore, average wind conditions are inherently biased. Wind velocities depicted via histogram exhibit left-skewedness due to the predominance of low wind speed values. Thus, average values derived from such data may not represent real-world

conditions. In addition, infrequent storm events, though occurring over a relatively short time span, are associated with strong winds. The effects of these events may remain even after the event has subsided. Moreover, when averaging wind directions, points on or near opposite ends of the circular compass rose may effectively cancel out or produce an unnatural directionality. Real-world directionality may hence be lost or inaccurately represented in monthly averages.

f.) To facilitate human conception of time, months (approximate 30-day intervals) are artificially imposed upon the natural system. Wind regimes clearly do not change immediately with the ending of one month and the beginning of another. Similarly, real-world strandings recorded early in a particular month are more likely to have been influenced by the wind and current regimes of the previous month (Bumpus 1973, Weber and Blanton 1980). Hence, the comparison of monthly averaged winds to monthly strandings warrants caution.

g.) The computer-generated drogue particles are considered to be without mass. Inertial effects, therefore, are not taken into account. The movement of a drogue on one day does not effect its behavior on the following day. Particles with large surface areas exposed at the water's surface (e.g., carcasses) are also more likely to be directly influenced by wind stress.

ii. Particle tracking model

The output of the flow field model served as the input of the particle tracking model, known as Drog3d (Blanton 1995). This model estimates Lagrangian motion experienced by hypothetical massless particles placed within a given flow field. The Drog3d program, written in Fortran, requires at least one of five files in order to generate

a simulated drogue track: nod, ele, gr2, din and vel. The nod and ele files provide the spatial coordinates of each node and element within the model domain, respectively (Blanton 1995). The gr2 file contains data on the interconnectivity of each node and element (Blanton 1995). The vel file includes the three dimensional responses of each node. A specific script in Matlab allowed for the conversion of the flow field response from a 2 dimensional (v2r) to a 3 dimensional (vel) format. The same steady state conditions that prevailed in the flow field model are also present within the particle tracking model. Wind stress magnitude and direction were constant in space and time over the entire model domain.

Parameters to vary within the oceanographic model domain included:

- a.) drogue sample size (n = 1-1500 per run)
- b.) initial drogue spatial location inside the model domain
- c.) initial drogue distribution (clumped, evenly-spaced, random)
- d.) wind conditions (monthly averages, daily averages)
- e.) current velocities (surface, mid-water, bottom, depth-averaged)
- f.) time spent drifting (hours, days, weeks, months)
- g.) presence or absence of M2 tide
- h.) running model forwards or backwards in time and space

Model drogues were released within pre-determined boundaries off of the computerized North Carolina coast and subjected to different monthly wind regimes. The lower boundary was determined by the resolution of the Werner et al. (1999) model along the coast. The smallest distance between adjacent nodes at the coastal margin was one kilometer. The 40 m isobath was selected as the upper boundary. Drogues that travelled seaward past the 40m isobath were then considered subject to forces beyond the predictive capabilities of the model (i.e., Gulf Stream effects).

Twelve runs were monitored, each corresponding to one month's wind stress values averaged for 15 years. Output from the particle tracking model was converted via the Awk programming script (Appendix 1) into the preferred format for ArcInfo (Charles Demas, personal communication). The model domain and drogoue particle tracks were converted into polygon and line coverages, respectively.

III. Stranding data acquisition, conversion and assumptions

Sea turtle stranding records from 1995-99 were obtained for North Carolina and were sorted by month (R. Boettcher, unpublished data). Excluding inshore strandings (e.g., sounds, rivers), the data were limited to ocean-beach events for all turtle species. Live stranded and cold-stunned individuals, however, were not included, as well as those turtles verified to have been entrained in power plant and dredge intakes. Only individuals meeting the aforementioned requirements were included in this study. Latitude and longitude coordinates of individual carcasses, originally recorded in degrees : minutes : tenths of minutes, were converted into decimal degrees. Spatial point locations were then entered into the ArcInfo GIS package. Corresponding point coverages were generated, built and ultimately viewed in geographic map projections.

It is assumed that ocean-beach stranding events represent mortality at-sea as opposed to inshore. At-sea mortality could be overestimated if turtles killed in inshore waters strand on beaches. Similarly, this could underestimate mortality if individuals killed in the ocean ultimately strand in sounds or other inshore waters. Although surface bottle drifters released in the shelf waters of the Middle Atlantic Bight have been recovered inside Pamlico Sound, these represented approximately 0.1% of the total

number of released drogues (13 of 11,052) (Harrison et al. 1967). Therefore, it seems likely, if oceanic carcasses strand, the majority will strand on ocean-facing beaches.

Officially reported carcasses provide point locations of stranded turtles. Because strandings are observed *a posteriori*, there is a possibility that some carcasses may have initially stranded at one location, become entrained into near-shore waters, and later sank or re-stranded at a different location. It seems likely that, if the time between primary and secondary stranding is relatively short, the original forces responsible for the initial stranding would carry re-stranded carcasses further downstream relative to the original site. Nonetheless, recorded spatial locations may not accurately reflect true stranding patterns.

Results

I. Winds (real-world)

Monthly averaged winds at Diamond Shoals from January to December for 1985-99 are shown in Table 2. Southeastern (northwesterly) and east-southeastern (west-northwesterly) winds predominated from November to February. General wind direction gradually shifted to the east (westerly) during March, April and May. A northeastern (southwesterly) wind pattern developed in June and July, followed by a north-northeastern (south-southwesterly) transition period in August. South-southwestern (north-northeasterly) winds persisted in September and October. Note that under southwestern water/northeasterly wind current regimes, Ekman transport could potentially move floating objects toward the coast (Weber and Blanton 1980).

Wind variability, however, was extremely high at the monthly scale. Standard deviations for monthly wind stress components were typically as large or larger than their corresponding mean values.

II. Near-shore surface currents (modeled)

Using the mean stress values in Table 2, vector flow fields were generated by the physical oceanographic model for each month. The flow fields represented residual changes in surface water movement predicted at model nodes in accordance with monthly wind patterns. Larger vectors signified larger differences in node responses to mean wind stress values. Likewise, small vectors indicated minor net differences in wind stress. However, such minor differences could exist between forces regardless of intensity.

Model responses off the North Carolina coast (Figures 5-16) have been organized according to five seasonal wind regimes, as described by Weber and Blanton (1980) for the South Atlantic Bight.

Winter (November-February, Figures 5-8)

Typically, during winter months, surface water regimes differed north and south of Cape Hatteras. South of the Cape, the model predicted offshore movement of surface waters. North of Cape Hatteras, however, the along-shelf component persisted through the winter months, where net water movement assumed a southward track.

Spring (March-May, Figures 9-11)

In contrast to the winter pattern, modeled conditions in March favored the development of northward along-shelf flow south of Cape Hatteras. The net water flow north of Cape Hatteras reversed direction from the winter months, also taking a

northward course. The model also predicted concentrated onshore flow along the eastern edges of the Carolina Bays.

Summer (June-July, Figures 12-13) and **Fall** (August, Figure 14)

The northward along-shelf surface flow persisted along the entire coast during these three months. In addition, net flow magnitude intensified throughout the region, peaking in July.

Mariner's fall (September-October, Figures 15-16)

In September, along-shelf flow reversed direction from its summer and fall course. This change in net direction was maintained through October, and later dissipated in November with the onset of offshore flow.

III. Lagrangian drogue floaters (modeled)

Monthly mean wind stress values were small in magnitude relative to real-world conditions. The resulting particle track distances of computer drogues released inside the model domain were thought to be artificially small, due to the preponderance of low wind stress magnitude values. The most likely explanation is that monthly stress magnitude values represent an inappropriate scale for particle tracking.

Several particle tracks were run using daily wind averages. Preliminary results showed that model drogues, backtracked from approximated real-world stranding point locations, remained shoreward of the 15m isobath.

IV. Sea turtle strandings (real-world)

Between 1995 and 2000, over 1300 turtles were recorded as having stranded on ocean-facing beaches of North Carolina (R. Boettcher, unpublished data). Almost half of these strandings occurred in May and June (Figures 17-18). In contrast, less than 8% occurred from December to February. Note that more than 75% of the strandings were recorded as members of *C. caretta*.

Furthermore, spatial locations of stranded carcasses demonstrated seasonal differences (Figures 19-30). During certain months, disproportionate numbers of carcasses stranded along the eastern stretches of Onslow Bay and Raleigh Bay. Using chi-square analyses, I tested the null hypothesis of uniform stranding distributions within these two cusped bays. I divided each bay into approximate halves by finding the straight-line distance between capes, locating the midpoint of that line, and drawing a perpendicular to the coast. I then simply counted the number of strandings within the eastern and western halves.

Statistical analyses revealed that carcass spatial distributions differed from those expected with random stranding patterns. Inside Onslow Bay, over 4 times as many turtles stranded along its eastern half compared to the western side (figure 31: $\chi^2 = 22.93$, $\chi^2_{\text{critical}} = 3.84$ at $\alpha = 0.05$). Similarly, for Raleigh Bay, I also found a significant difference in stranding patterns (figure 32: $\chi^2 = 4.83$, $\chi^2_{\text{critical}} = 3.84$ at $\alpha = 0.05$), though it was not as prominent as for Onslow Bay.

increased during the spring (from March to May), when the model predicted the development of the along-shelf current. During the winter north of Cape Hatteras, however, an established southern longshore current was present despite few strandings. Epperly et al. (1996) argued that the number of turtle carcasses stranded in proximity to the southern flounder trawl fishery was not a reliable indicator of turtle mortality at-sea.

There are several alternative explanations for decreased strandings recorded in winter:

a. Migratory patterns and turtle distributions

There may be fewer turtles available to strand, or more turtles may reside further offshore, during the winter months. Recall that large juveniles and small sub-adults compose the majority of strandings in North Carolina and Virginia (Crouse et al. 1987, Lutcavage and Musick 1985). In temperate regions, large juveniles tend to occupy near-shore demersal habitats (Musick and Limpus 1997). During the fall in the western temperate Atlantic, juveniles migrating through the waters off North Carolina from northerly foraging areas (e.g., Chesapeake Bay) travel approximately within 20 km of the coast (Musick and Limpus 1997). In contrast, during January and February, most loggerheads remaining in North Carolina waters are found along the western wall of the Gulf Stream (Epperly et al. 1995), having migrated from cooler inshore waters to warmer offshore waters (Murphy and Hopkins-Murphy 1989).

b. Poikilothermy

Cold winter temperatures may translate into relatively longer drowning times for air-breathing poikilotherms (Murphy and Hopkins-Murphy 1989). During the winter, reduced water temperatures decrease turtle metabolism, which in turn leads to decreased

O₂ consumption. Sea turtles may be physiologically predisposed to better withstand forced submergence, associated with anthropogenic trawling, during colder conditions.

c. Decreased trawling effort or spatially displaced effort

Fewer turtles may be being killed or turtles may be being killed at greater distances from the shore. Despite lack of direct evidence of a causal relationship, researchers were able to provide proximate evidence that strongly suggests a relationship between strandings and the initiation of the shrimp trawl season in South Carolina (Murphy and Hopkins-Murphy 1989, NRC 1990, Crowder et al. 1995). The Atlantic shrimp trawl season, typically beginning in April or May, is largely inactive during winter months. If winter fisheries implicated with turtle bycatch move to more distant offshore locations, fewer carcasses would be likely to strand.

d. Landward shift of Gulf Stream

Though highly variable in space, the Gulf Stream is generally closer to the coast during winter months. Carcasses floating in shelf waters during the winter may be more likely to be entrained into the Gulf Stream. It has also been hypothesized that near-bottom waters move offshore to re-establish equilibrium during winter months (Schumacher 1974).

iii. Trend 3: Clumped distributions of strandings along eastern edges of cusped bays

There is evidence that carcasses do not strand uniformly along the Carolina Bays during May and June. Recall that the oceanographic model predicted relatively greater magnitudes of onshore flow for the eastern halves of the Carolina Bays. Variable observer effort, however, could also explain this trend.

iv. Trend 4: relationship between net flow direction and spatial location of mortality

On average, according to modeled surface currents, carcasses having stranded from April through August most likely floated from positions to the south of their recorded locations. Conversely, from September through November, the model estimated net southward flow, indicating that mortality sources were probably located to the north. It seems likely that floating carcasses would follow the direction that the water mass flows, regardless of the rate of decomposition and longevity of buoyancy. Providing a crude estimate of the spatial direction of mortality, the model could at least be used to exclude potential downstream mortality sources during periods of sustained unidirectional along-shelf flow.

Running the particle tracking model backwards (using daily instead of monthly averaged stress values) resulted in most drogues remaining within the shallowest bathymetric zones, due to the prevalence of strong along-shelf flow. Whether or not this phenomenon is an artifact of the model is important for future researchers to discern. If accurate, then real-world carcasses that strand may represent a subset of turtles killed in only the closest of waters to the shore. In continental shelf dynamics, the magnitude of the along-shelf component is characteristically greater than that of the cross-shelf component (Hare et al. 1999).

v. Trend 5: Association of August-September wind transition to stranding patterns

The transition from north-northeastern currents in August to south-southwestern currents in September in the region has been documented by physical oceanographers (Harrison et al. 1967 for the Chesapeake Bight, Bumpus 1974 for the South Atlantic Bight). The reversal in direction is thought to be counterclockwise in orientation (Weber

and Blanton 1980). All else being equal, it seems reasonable that relatively more strandings would occur during such a shift, due to the predominance of onshore winds. However, few strandings are typically reported for Onslow Bay and Raleigh Bay from August to September (see also Figures 26-27). This would imply, then, that during September either a.) there are few turtles off southern North Carolina, b.) there are fewer mortality sources in the region, or c.) mortality sources are present but located further offshore.

II. Estimating landfall probability via surface drift-bottle recovery patterns

In a long-term drift study, Bumpus (1973) demonstrated poor recovery rates of drogues released from November to February within the Middle and South Atlantic Bights. From 1960-70, 165,566 ballasted surface drift-bottles (e.g., 8 ounce soda bottles) were released at 78 locations widely distributed over the continental shelf (25-44° N, 64-81° W). Low recovery rates recorded during winter months led Bumpus to infer that offshore surface drift was largely responsible for the paucity of recovered drifters. Because bottom drifters, released simultaneously with surface drifters, were being reported regularly throughout the year, Bumpus believed that the seasonal patterns of surface drifter return were not an artifact of observer bias (Bumpus 1973).

In a similar project, Harrison et al. (1967) released surface drift bottles (N = 11,052) at distances inside the Chesapeake Bight, a 300+ km extent of the southern Middle Atlantic Bight stretching between Cape Henlopen, Delaware and Cape Hatteras, North Carolina (Figure 4). In accordance with Bumpus' findings, they confirmed that drifter returns from June 1963 to October 1964 demonstrated monthly variation. During

the winter of 1963-64, less than 1% (16 out of 2592) of the bottles released over the entire study area were ultimately recovered. Harrison and colleagues hypothesized that northwesterly winds, prevailing from late November into February, tended to move waters offshore and to the south. During the rest of the year, large numbers of drifter recoveries most often coincided with periods of onshore winds (Harrison et al. 1967). Regardless of monthly variation, the majority of drifters were recovered within approximately 2 weeks. Furthermore, percent recovery of surface drift-bottles was strongly related to increased distance released from shore. This relationship was strongest during the summer, moderate during spring and fall, and weakest during the winter (monthly returns provided in Figures 33-36 represent four climatological seasons).

There are a few cautions, however, in comparing the behavior of bottle recoveries to turtle strandings:

- a.) The difference in size may make stranded turtles easier to detect on shore.
- b.) Increased surface area of floating turtles could provide greater area for wind stress to directly act upon.
- c.) Air and sea surface temperature should have little effect on bottles, but could drastically alter the time spent afloat for carcasses (i.e., facilitating or inhibiting bacterial growth and activity).
- d.) Context dependency of the Harrison et al. (1967) experiment: it is conceivable that drifters could behave in a fashion specific to the properties of the Chesapeake Bight.

Despite potential biases, the landfall probabilities extrapolated from drift bottle experiments may have direct relevance to turtle management. There is a finite period of time available for carcasses to float, whereas the time window is theoretically infinite for uncompromised drift bottles (i.e., unbroken, with little or no epifauna). It seems reasonable that drift bottles could provide an upper bound to describe a.) how far

carcasses could theoretically travel and b.) how likely those carcasses could make landfall from points offshore.

III. Carcass decomposition

In a study by Mann et al. (1990), ambient air temperature had the greatest effect on the decomposition rate of human cadavers. Greater enzymatic efficiency may be associated with warmer temperatures, whereas low temperatures may delay or stop the decay process entirely. In the same study, the researchers also found that the rate of decomposition is most difficult to ascertain during months with the greatest degree of temperature fluctuation. Despite the physiological differences between mammal and reptile carcasses, it is reasonable to assume that the abiotic factors affecting decomposition of large vertebrate species on land may be similar to those in marine environments. High air and water temperatures may facilitate bacterial growth, leading to a more rapid increase in carcass buoyancy while inhibiting the duration of carcass buoyancy (i.e., the amount of time spent floating at the surface). Turtles experiencing mortality during the warmer months may achieve buoyancy faster, but may remain buoyant for less time, relative to individuals killed during colder months. Bacterial decomposition over time may also make a carcass less palatable for some marine scavenging species (Britton and Morton 1994), thus slowing the rate of tissue loss attributable to scavengers. Terrestrial mammalian carcasses that have undergone gross trauma will typically decay at a faster rate than bodies without such injury (Mann et al. 1990). The presence of penetrating wounds could also translate into decreased time of buoyancy. Such wounds would likely increase the surface area available to decomposers

and scavengers, ultimately decreasing the time to carcass disarticulation. The absence of wounds made via scavenging may indicate that a carcass has been exposed to the ocean for a relatively brief time or a scarcity of scavengers in the region (Mann et al. 1990).

IV. Anthropogenic interactions with sea turtles

Scientists have yet to quantify to what extent, if any, turtle deaths in one area are influenced by fishing pressure in another. Historically, turtle mortality has been blamed on fishers closest in space to a particular stranding site and closest in time to a particular stranding event.

Incidental death via shrimp trawling has been cited as the most important source of anthropogenic mortality for sea turtles in U.S. waters (NRC 1990). A positive relationship between tows duration and turtle mortality has been documented (Henwood and Stuntz 1987). The outcome of longer trawls (> 90 minutes) shows 70% of captured individuals are likely to be dead or comatose (Henwood and Stuntz 1987, Lutcavage et al. 1997). Although trawls of short time periods (< 50 minutes) result in negligible turtle mortalities, the turtles captured during these periods possessed high levels of lactic acid (Henwood and Stuntz 1987). Turtles residing in waters with intensive trawling are more likely to be exposed to repeated captures (Murphy and Hopkins-Murphy 1989). Such events make turtles more susceptible to anaerobic shock and ultimately death, in spite of TED use by fishers (Lutcavage et al. 1997). The majority of commercial shrimp species occur abundantly in relatively shallow depths along the Atlantic coast of the Southeast U.S.: *Penaeus aztecus aztecus* or brown shrimp (less than 55 meters), *P. setiferus* or white shrimp (less than 17 meters) and *P. duorarum duorarum*

or pink shrimp (10-37 meters) (Murphy and Hopkins-Murphy 1989). Because approximately 92% of Atlantic shrimp fishery effort occurs within 5km of shore (NRC 1990), it seems reasonable that the majority of shrimping activity by fishers occurs on the continental shelf.

The second-most important human-related source responsible for sea turtle mortality is attributed specifically to non-shrimp fisheries and generally to unattended nets set in shallow waters (NRC 1990, Lutcavage et al. 1997). Epperly et al. (1995) estimated that more than 1,000 turtles were caught, including a disproportionate number of *L. kempii*, in the Summer Flounder trawl fishery off North Carolina from November 1991 to February 1992. Monkfish (*Lophius americanus*) and Spiny Dogfish (*Squalus acanthias*) large-mesh sink gillnet fisheries accounted for almost 80% of sea turtle takes officially documented by the NMFS Observer program in North Carolina waters (Carolyn Steve, personal communication). Both fish species are demersal and their ranges extend from the pelagic zone into coastal shallows.

Of the 1376 turtle carcasses recorded as having stranded on ocean-facing beaches from 1995-1999 in North Carolina, only 148 carcasses (10%) retained recognizable signs of human interaction (R. Boettcher, unpublished data). Approximately 55% of these had damage synonymous with propeller wounds from boat collisions (R. Boettcher, unpublished data), attributable to commercial and recreational boats. Other sources of human interaction included entanglement in passive fishing gear (19%), precision removal of carapace, head or appendages (15%), dredging entrainment (4%), gunshot wounds (2%) and non-fishing-related pollution (1%) (R. Boettcher, unpublished data). However, because injury infliction was not directly observed, it is likely that an unknown

proportion of turtles received some damage post-mortem. Both dead and live turtles can become entangled in gear or receive prop wounds. Furthermore, anthropogenically wounded turtles may survive for an indefinite period of time before ultimately succumbing, and, in that time, may actively travel far from the initial source of mortality. Healthy juveniles artificially displaced over 100 km demonstrated strong site fidelity, traversing the distance within a few weeks (Keinath et al. 1987). Note that the vast majority of stranded carcasses show no external signs of injury or are in such decomposed states that any sustained injuries are from undetermined sources.

V. Closing remarks

I am confident that the flow field model accurately predicts near-shore currents that turtle carcasses could be entrained in, shoreward of the 40m isobath. However, it is important for me to clarify the limitations of applying the oceanographic model to sea turtle stranding patterns. This project does not imply that it can predict the locations of specific stranding events or specific mortality sources. However, by using monthly flow fields predicted by the model and by relying on empirical evidence from surface drift-bottle experiments, this work can describe large-scale seasonal patterns in North Carolina.

Several general trends were observed:

i. Temporal stranding patterns

Carcasses could be more likely to strand from March to October due to the development and persistence of an along-shelf current parallel to the coast. Likewise, carcasses seem least likely to strand from November to February due to the presence of offshore flow.

ii. Spatial stranding patterns

Turtle carcasses do not strand in uniform spatial distributions during peak stranding months along the ocean-beach coast of North Carolina.

iii. Spatio-temporal patterns of mortality

Relative to their recorded stranding position on the beach, sea turtles are more likely to have been killed in areas to the south (from April to August) and to the north (from September to October) due to the net direction of along-shelf flow.

iv. Carcass landfall probability

Surface drift-bottle experiments reveal that a.) there are seasonal patterns of recoveries and b.) percent recovery is correlated with distance from shore. It makes intuitive sense that an object released further from shore will have a lower probability of making landfall compared to an object released closer to shore. On average, the number of carcasses stranded on ocean-facing beaches may represent, at best, approximately 20% of the total number of available carcasses at-sea. This evidence, in accordance with the spatial behavior of modeled lagrangian drogues, indicates that turtles only killed very close to the shore may be most likely to strand.

Stranding analysis requires an interdisciplinary approach. Discerning how the number of turtles stranded on the beach is related to the number of carcasses at-sea will help sea turtle managers develop more accurate estimates of actual mortality rates. This research may at least be able to identify seasons when turtles are not likely to strand. It also provides evidence to sea turtle managers that incidental stranding limits (ISLs) need to be calculated on a seasonal basis, in light of oceanographic conditions. Such

information could then be applied to create more accurate time closures or area closures for fisheries with historic bycatch interactions with turtles.

The correlation between seasonal net along-shore flow and greater relative numbers of stranded carcasses warrants further study. The dynamics of turtle carcasses free-floating in the water column have not been quantitatively studied. Decomposition experiments could help determine the physical conditions required for sea turtle carcasses to sink, bloat and float, as well as assess the total duration of this process. Using such data, algorithms can be created to model generalized carcass behavior. Moreover, the creation of finer resolution in finite element matrices will increase the potential accuracy of oceanographic models. Recall that the Werner et al. (1999) flow field model best estimated water movement between the 40m isobath (beyond which Gulf Stream effects increase) and 1km (lowest inter-node resolution along the coast) (Hare et al. 1999). Ground-truthing work comparing empirical behavior of field drifters to modeled behavior of computer drogues will also serve to troubleshoot model output.

Estimating mortality is an important component of demographic analyses, having added consequence for threatened and endangered species. Population biology and physical oceanography have, until recently, been scientific fields with little crossover. Hopefully, collaborative projects such as this will continue in the future.

Though qualitative, this research a.) provides a starting point for more robust analyses and b.) demonstrates that stranding research requires an understanding of ocean physics in addition to sources of mortality.

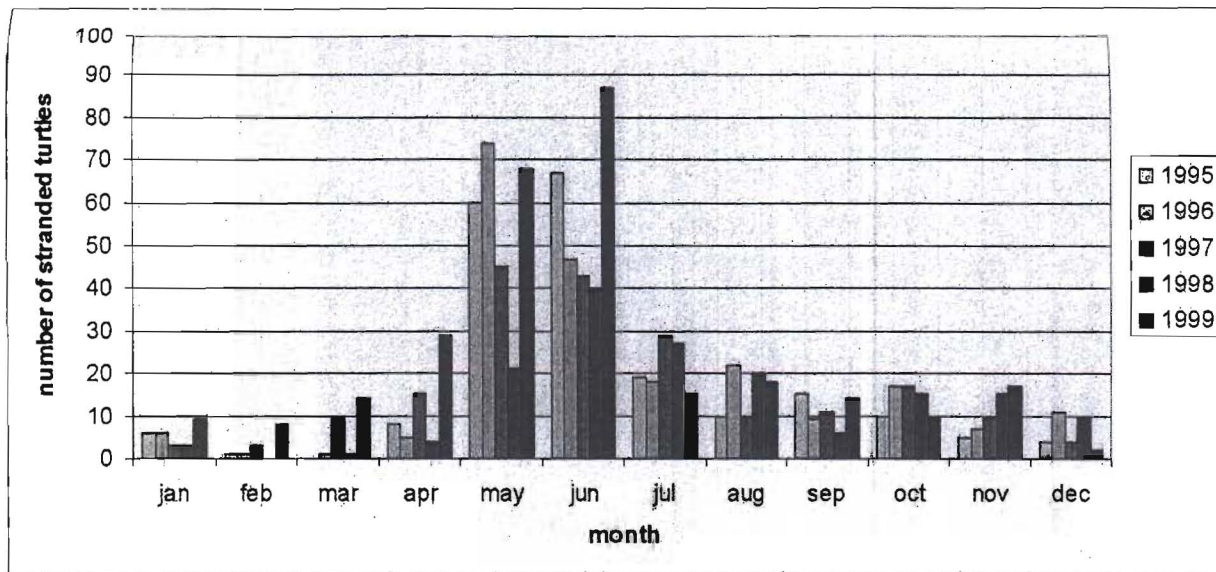


Figure 1. Ocean-beach strandings of *Caretta caretta* in North Carolina summed by month and sorted by year (derived from unpublished data provided by R. Boettcher).

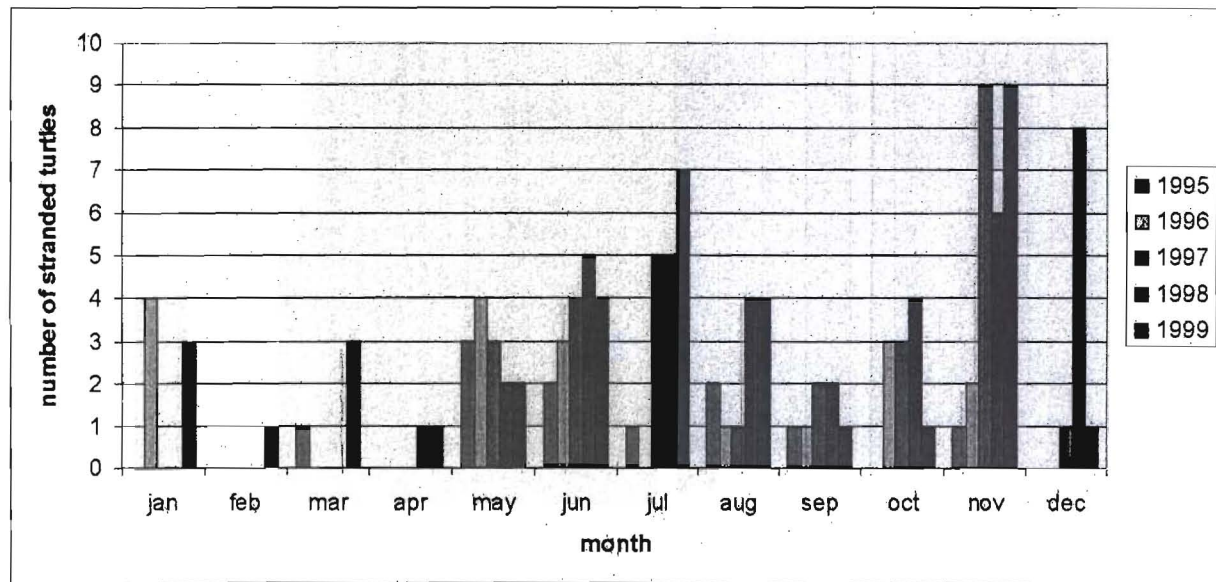


Figure 2. Ocean-beach strandings of *Lepidochelys kempii* in North Carolina summed by month and sorted by year (derived from unpublished data provided by R. Boettcher).

Table 1. Potential biases and limiting factors associated with analyses of sea turtle carcasses and strandings (from Harrison et al. 1967, Murphy and Hopkins-Murphy 1989, Mann et al. 1990, Britton and Morton 1994, Crowder et al. 1995, Epperly et al. 1996, Coles and Musick 2000)

Abiotic

Water and air temperature

Increase or decrease longevity of intact carcass

Increase or decrease time to achieve buoyancy via microbial activity

Seasonal wind regimes and net water movement

onshore flow may promote strandings

offshore flow may preclude strandings

Seasonal riverine input

Pressure gradients may cause mixing

M2 tidal oscillation

Biotic

condition of carcass

presence or absence of penetrating wounds may affect carcass longevity

relative numbers of scavengers in region

variability of microbial activity

body size

physiological state prior to death

seasonal differences

sexual dimorphism

spatio-temporal distributions of turtles prior to death

species-specific migratory patterns

upper and lower thermal limits

non-random distribution at-sea

convergence zones/western wall of Gulf Stream

spatial source of mortality

nearshore versus pelagic

mobile or stationary

seasonal or year-round

natural or anthropogenic

Anthropogenic

dynamic fishing effort

variable observer effort

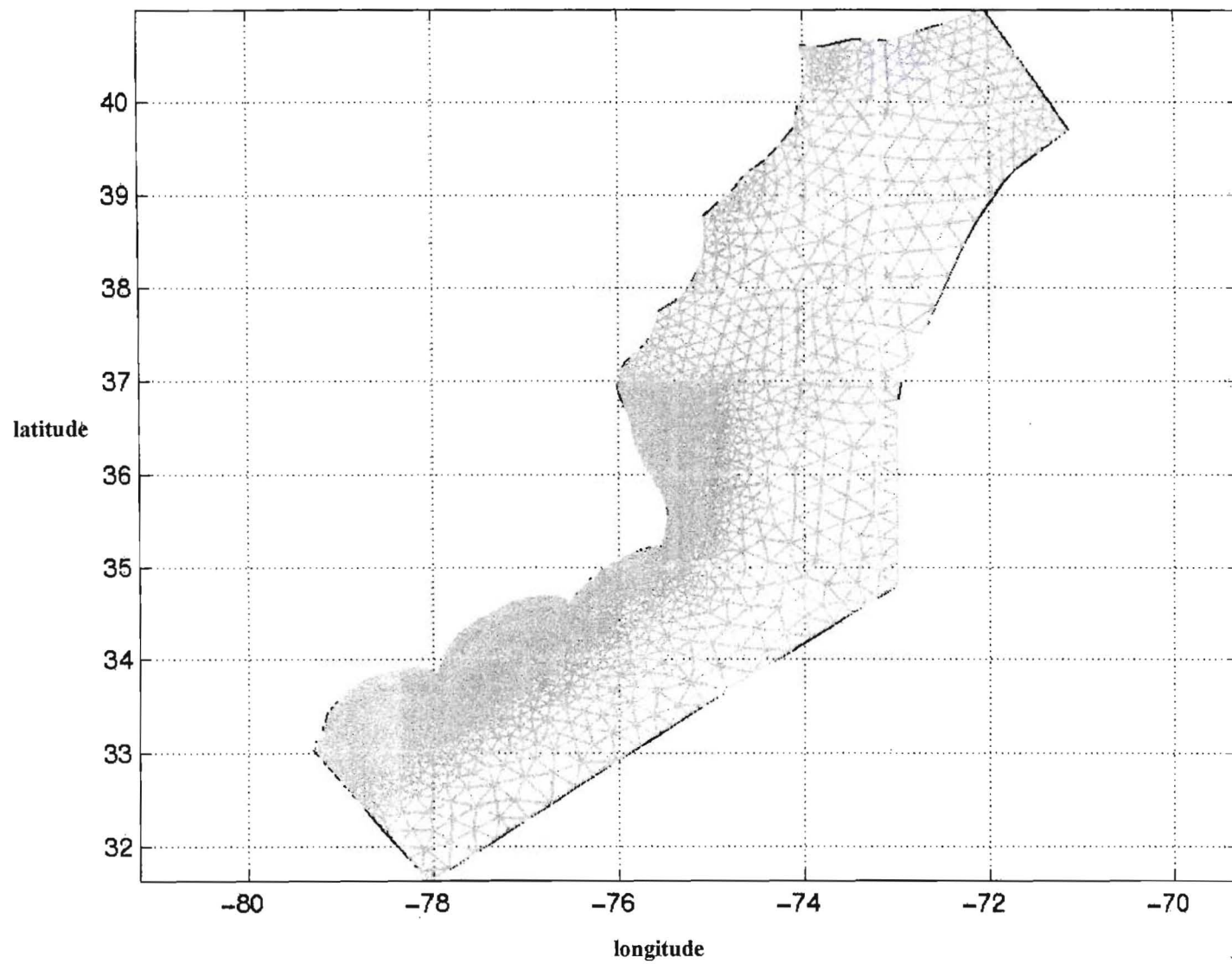


Figure 3. Finite element matrix of the Werner et al. (1999) physical oceanographic model, composed of 3335 nodes interconnected by 6416 elements.

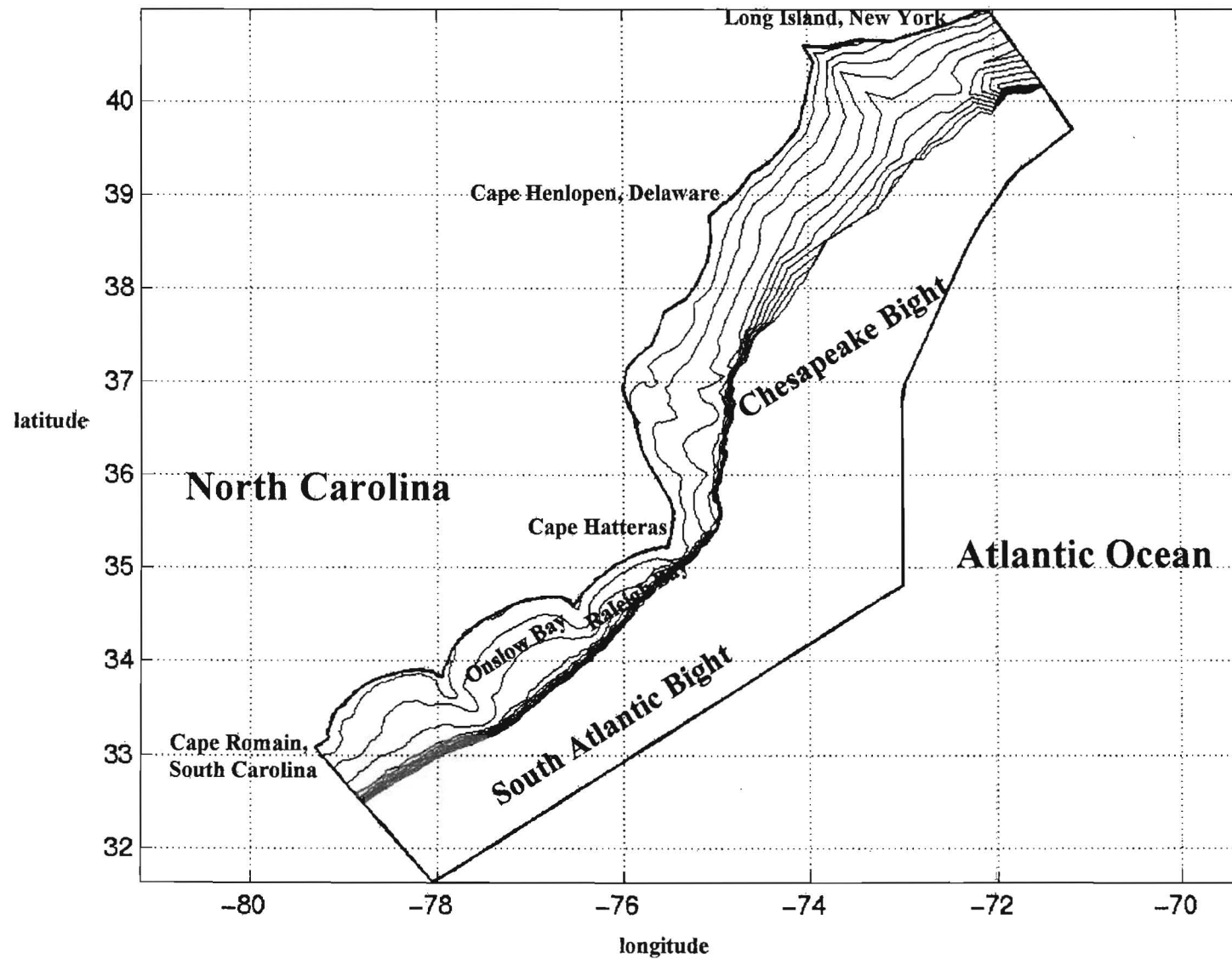


Figure 4. Spatial domain of the Werner et al. (1999) model with geographic locations used in the text. Isobaths (shown in red) are in 10 meter increments, ranging from 10 to 100 meters.

Appendix 1: Awk script (C. Demas, personal communication)

```

BEGIN{num_drogues =x; groupcn t=y}
{group=((NR-1)%num_drogues)+1}
cnt=1+int((NR-1)/num_drogues)
a[group,cnt]=$0}
END{for(i=1; i<num_drogues;i++){
print groupcnt++", "
for(j=1;j<=cnt;j++){
print a[i,j]}
print"END,"}}
print"END"}

```

NB: select desired values for num_drogues (i.e., total drogue number for one model run) and groupcnt (i.e., starting number for unique ids).

Table 2. Monthly averaged wind stress magnitude and stress direction values at Diamond Shoals (Cape Hatteras, North Carolina) from 1985 to 1999. Wind stress direction is presented in degrees clockwise from true North in oceanographic convention (i.e., direction flowing to).

Month	Magnitude (dynes/cm ²)	Direction (degrees)	Direction (bearing)	Sample size (# of hourly recordings)
January	0.127	127.3	E-SE	11360
February	0.113	139.3	SE	9923
March	0.049	123.4	E-SE	11114
April	0.052	92.9	E	11426
May	0.025	86.7	E	11758
June	0.055	47.9	NE	11370
July	0.194	48.3	NE	11126
August	0.010	39.5	N-NE	9746
September	0.008	218.8	S-SW	10041
October	0.061	197.2	S-SW	10278
November	0.039	138.1	SE	10198
December	0.172	141.9	SE	10884

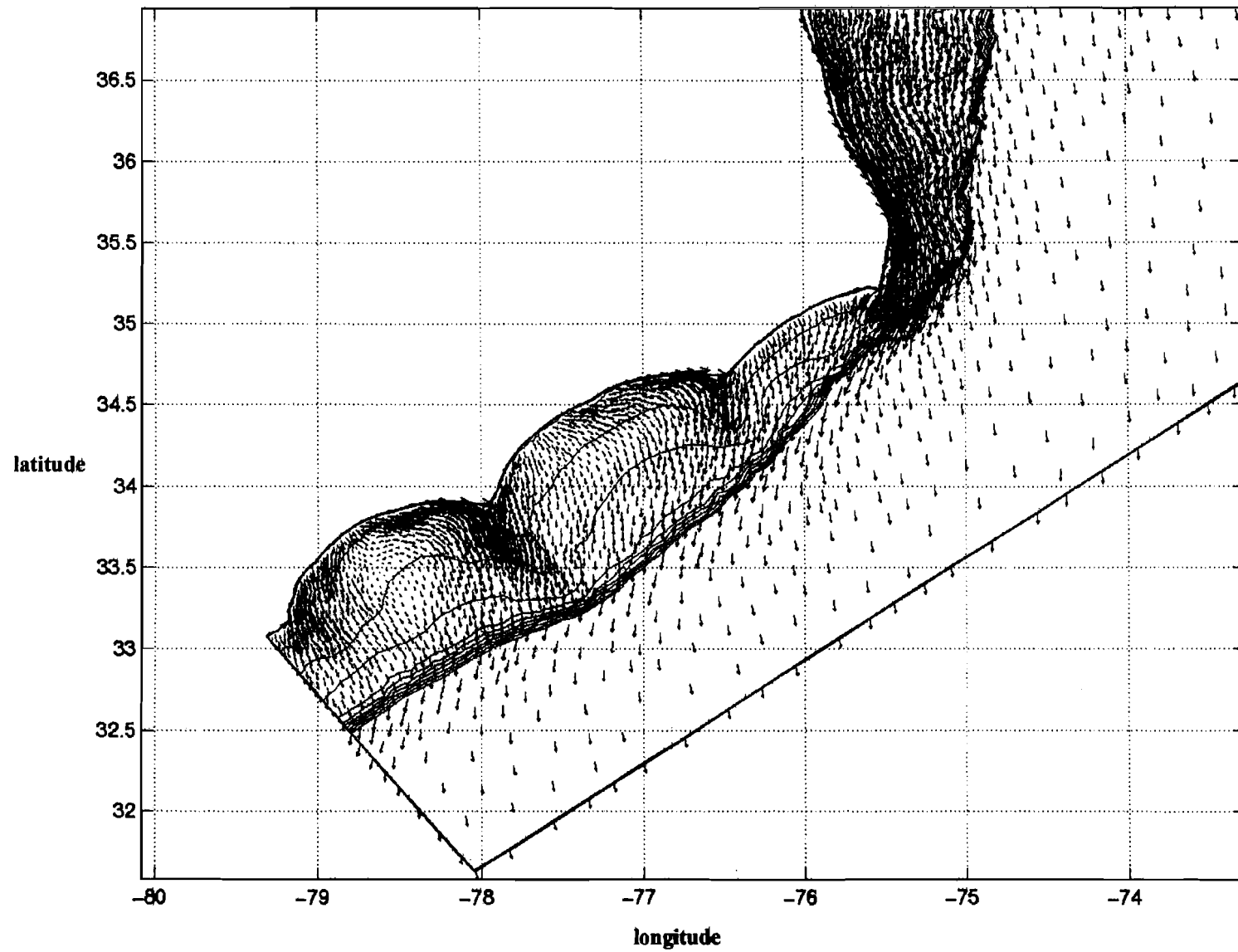


Figure 5. Model surface response to average November conditions

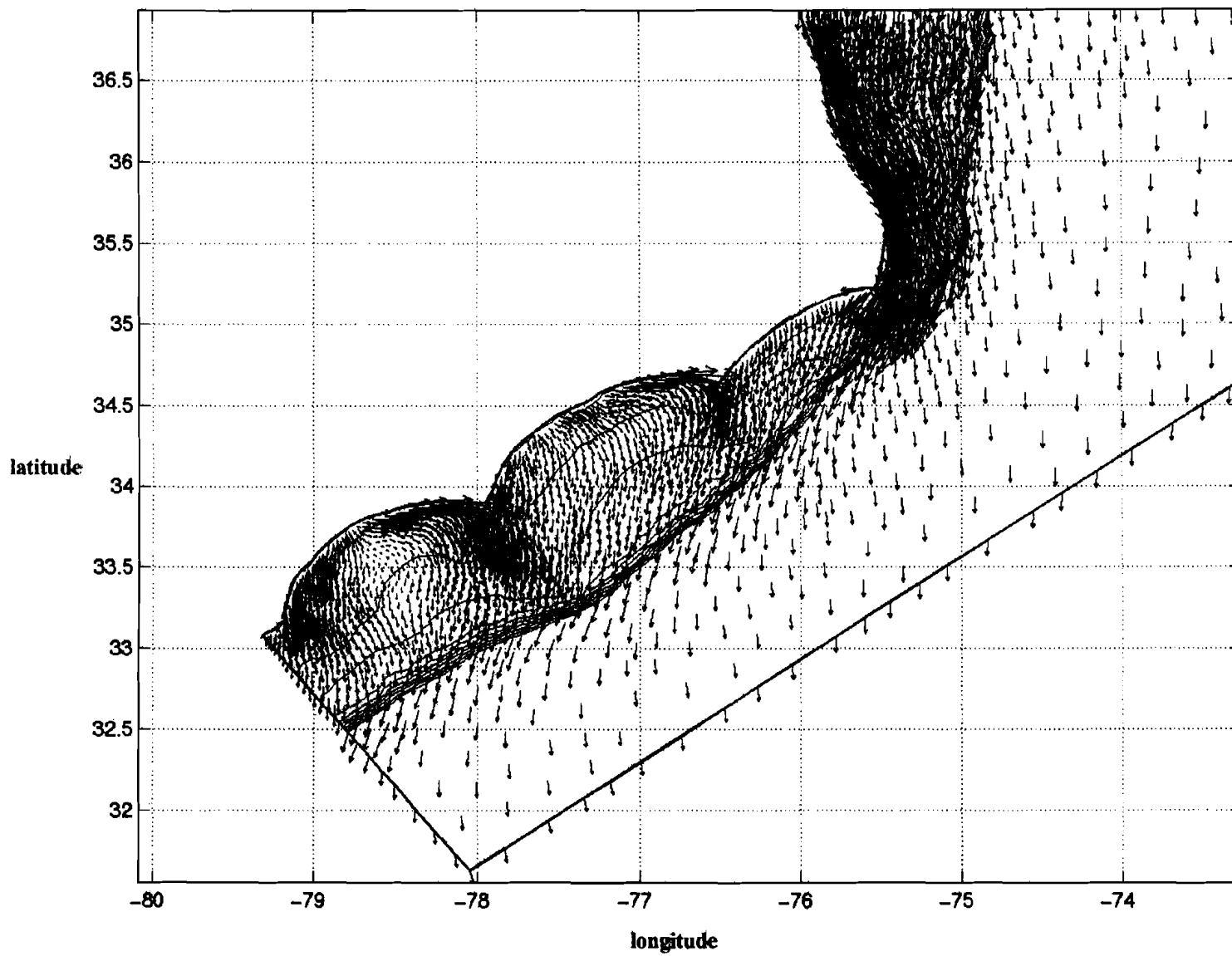


Figure 6. Model surface response to average December conditions.

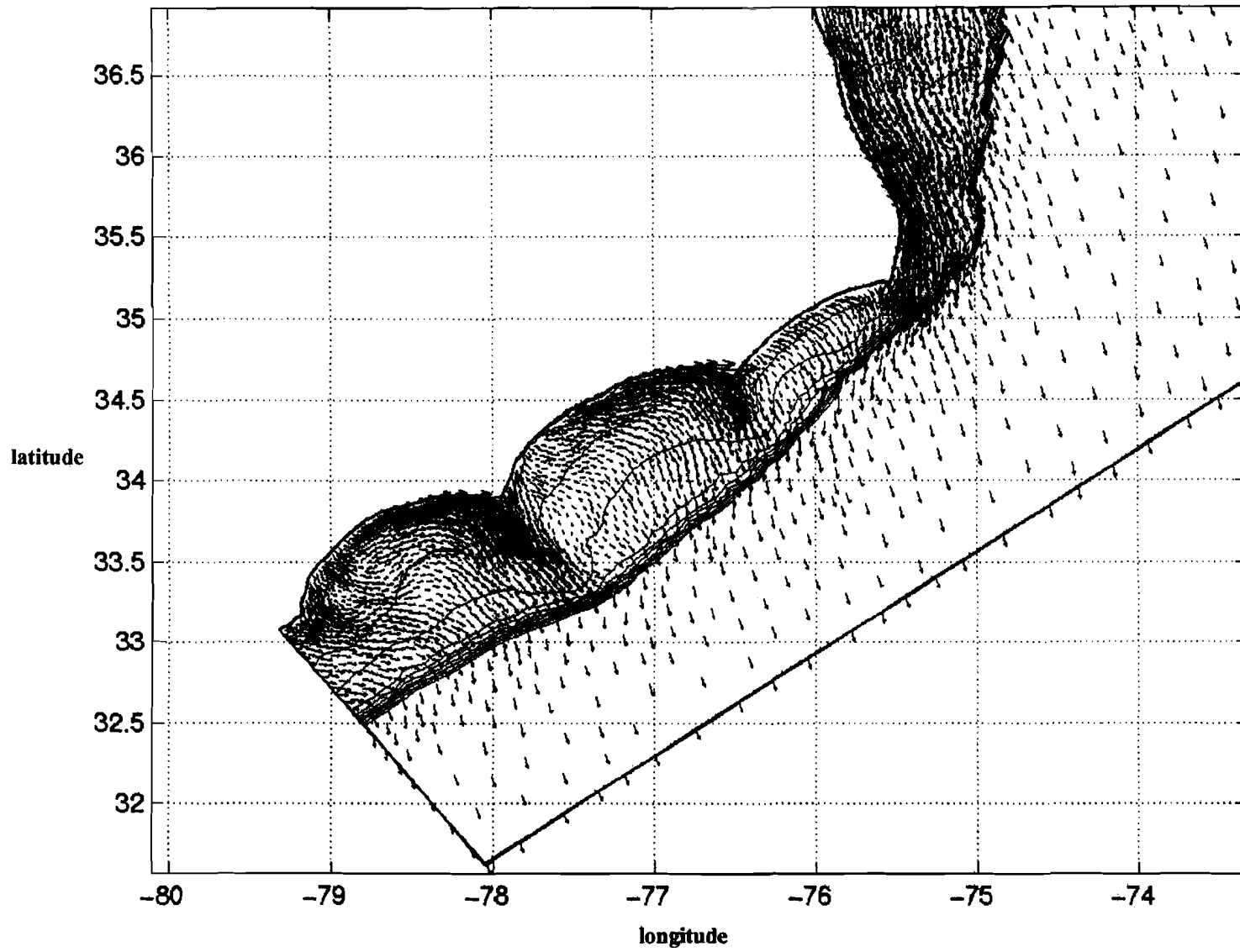


Figure 7. Model surface response to average January conditions.

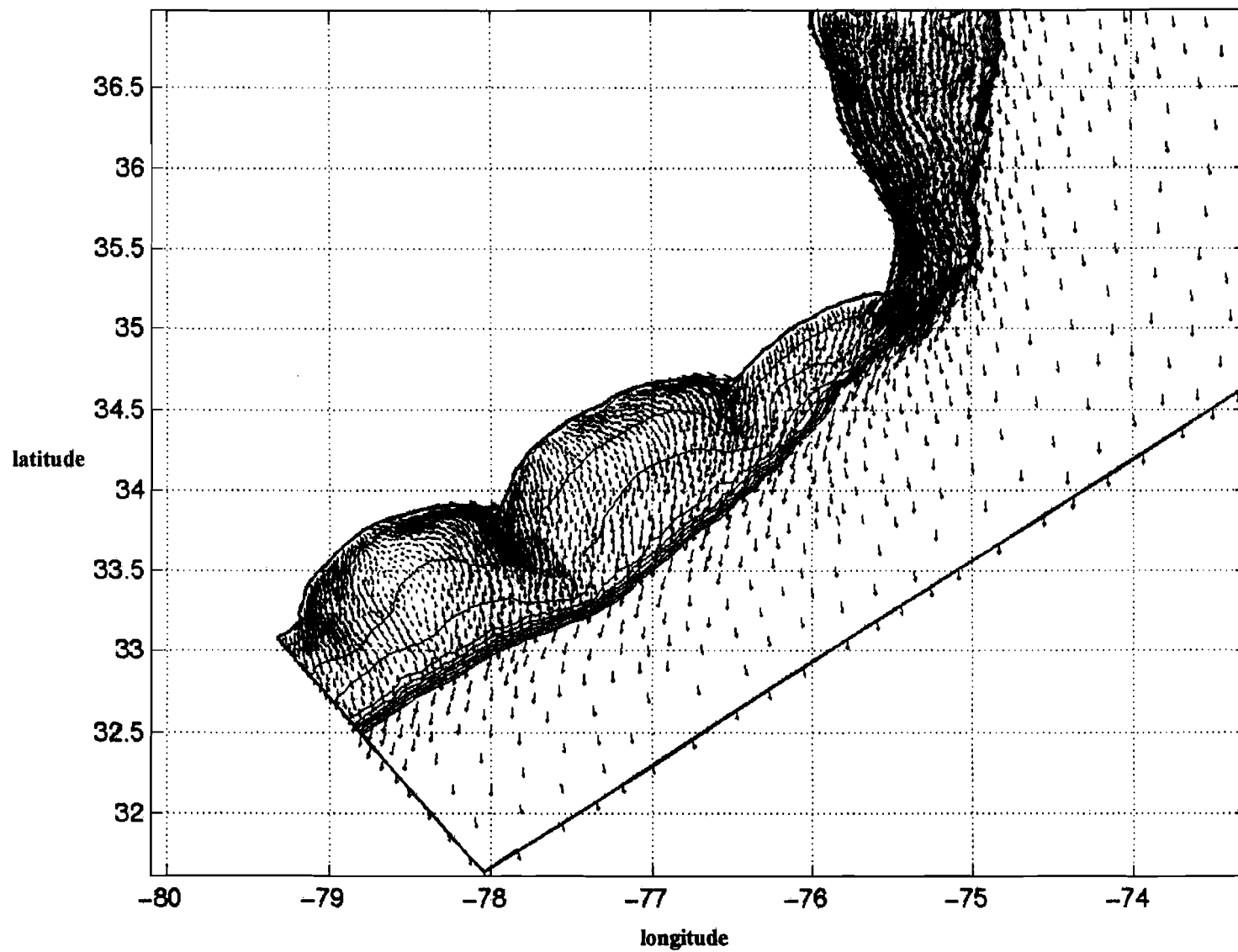


Figure 8. Model surface response to average February conditions.

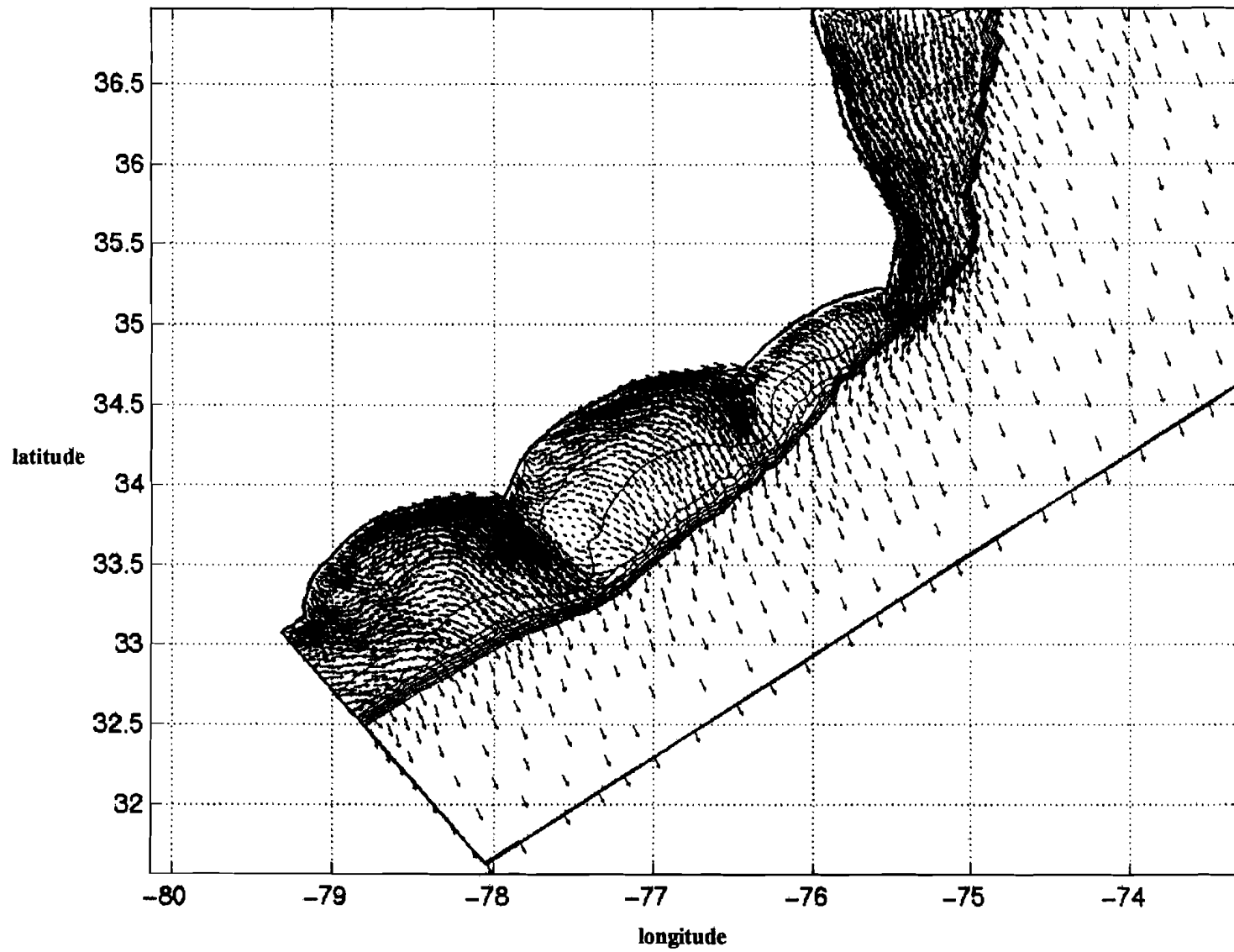


Figure 9. Model surface response to average March conditions.

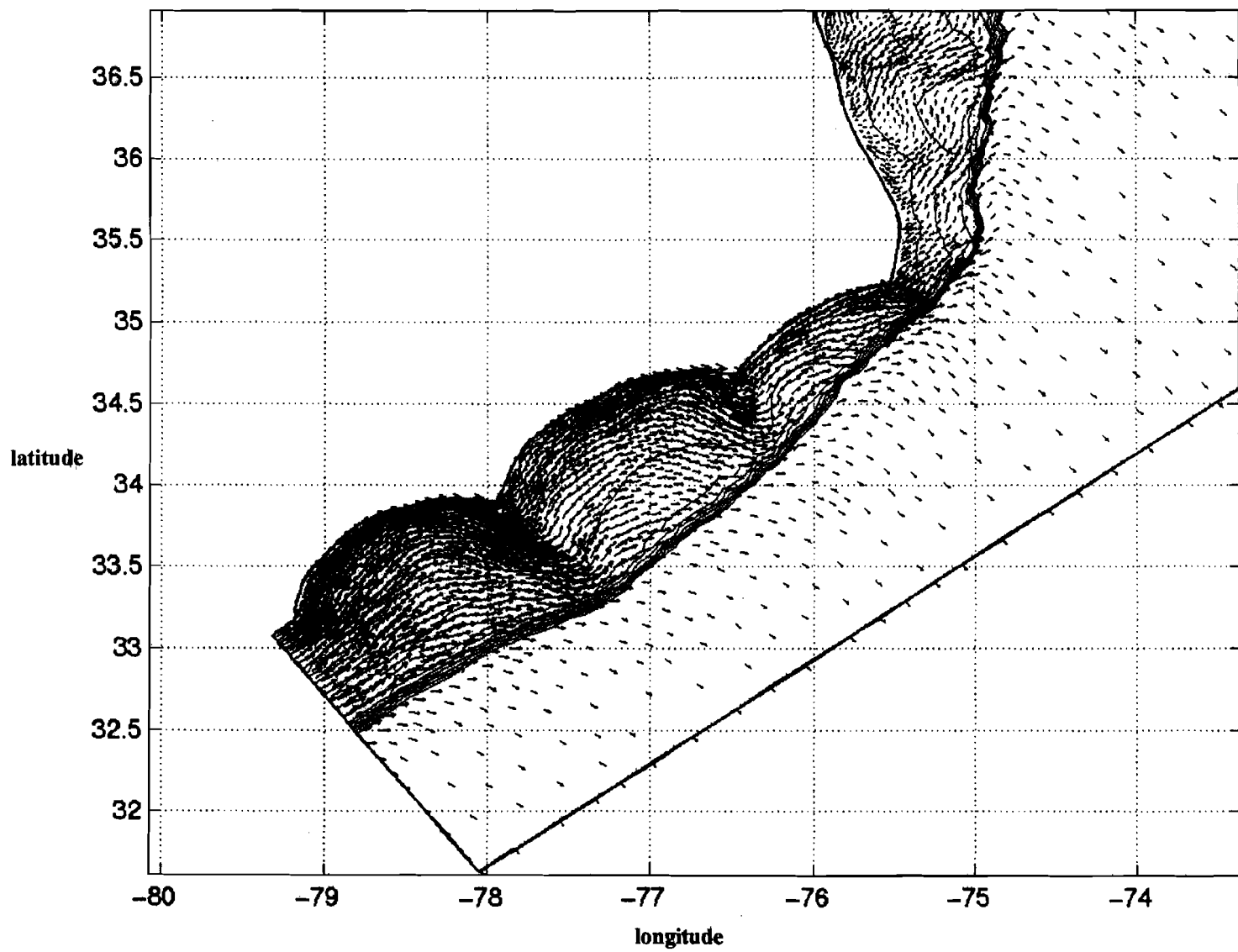


Figure 10. Model surface response to average April conditions.

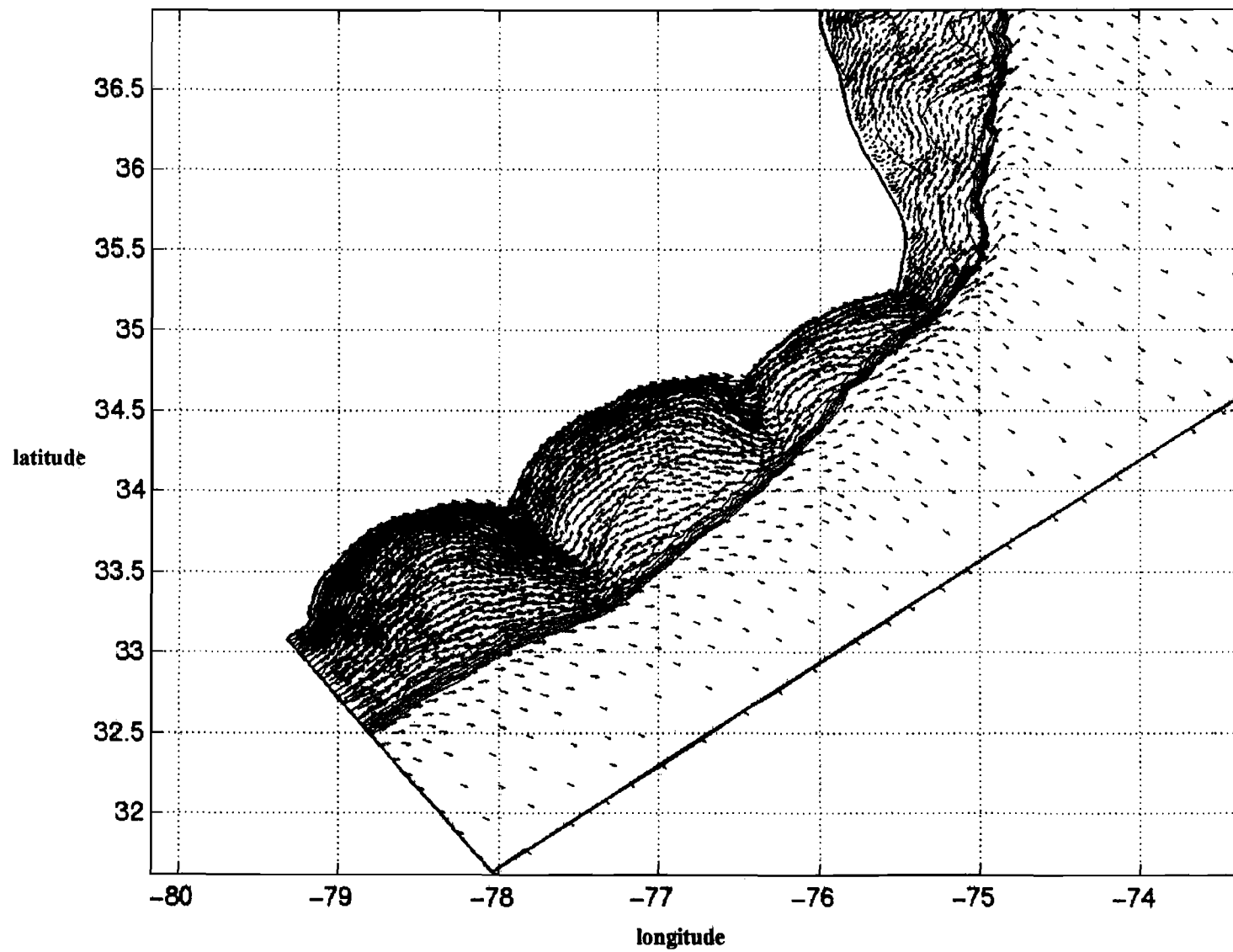


Figure 11. Model surface response to average May conditions.

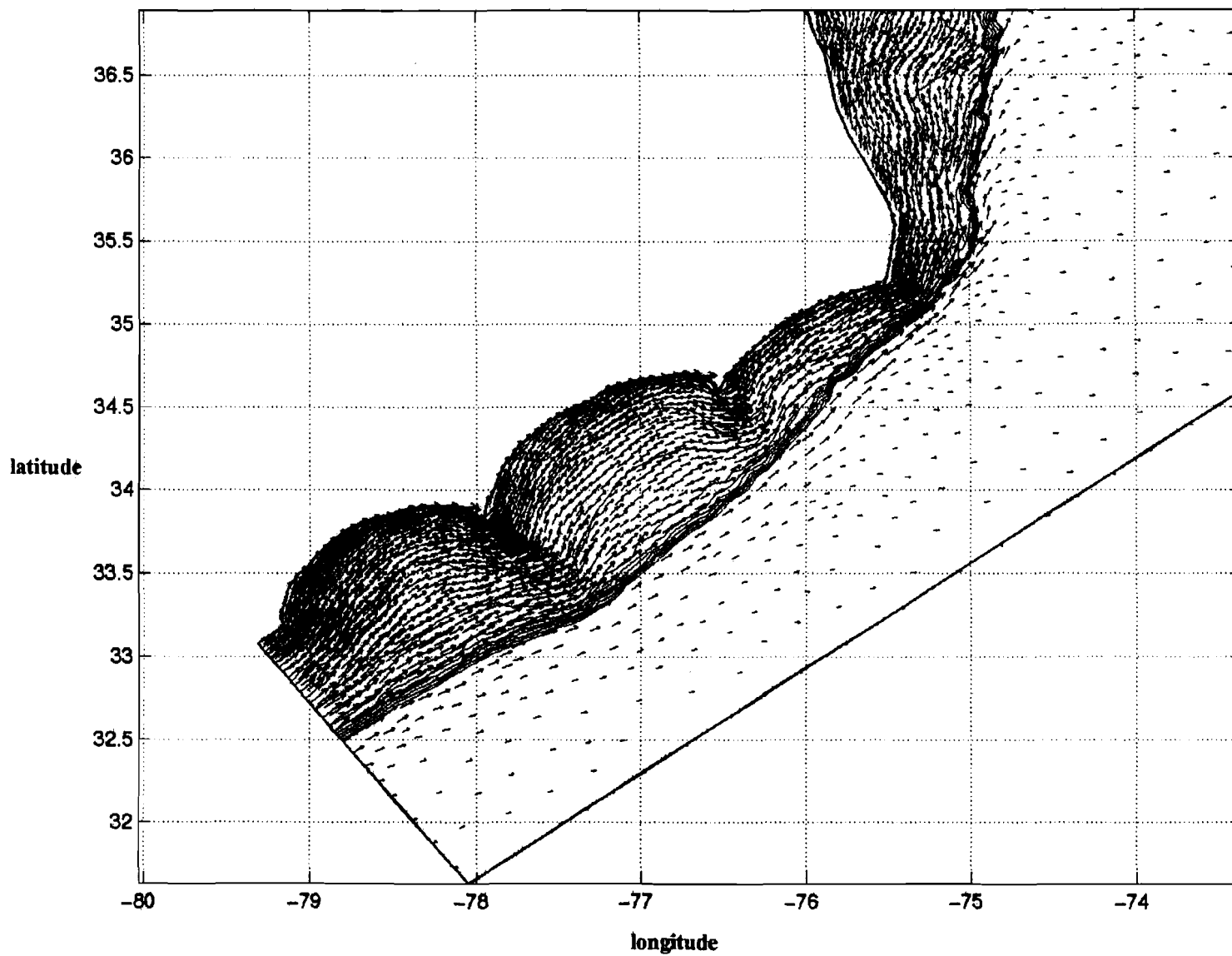


Figure 12. Model surface response to average June conditions.

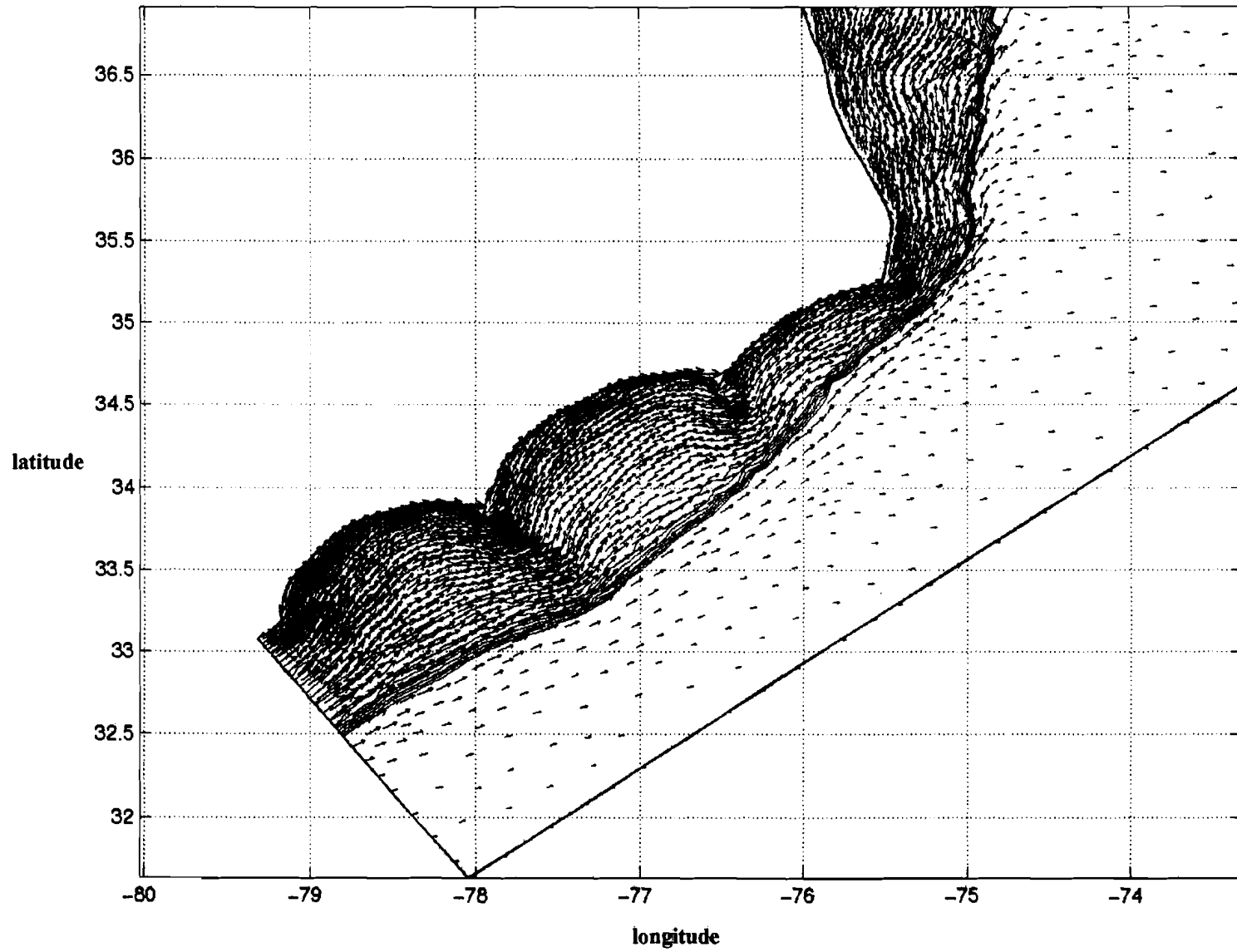


Figure 13. Model surface response to average July conditions.

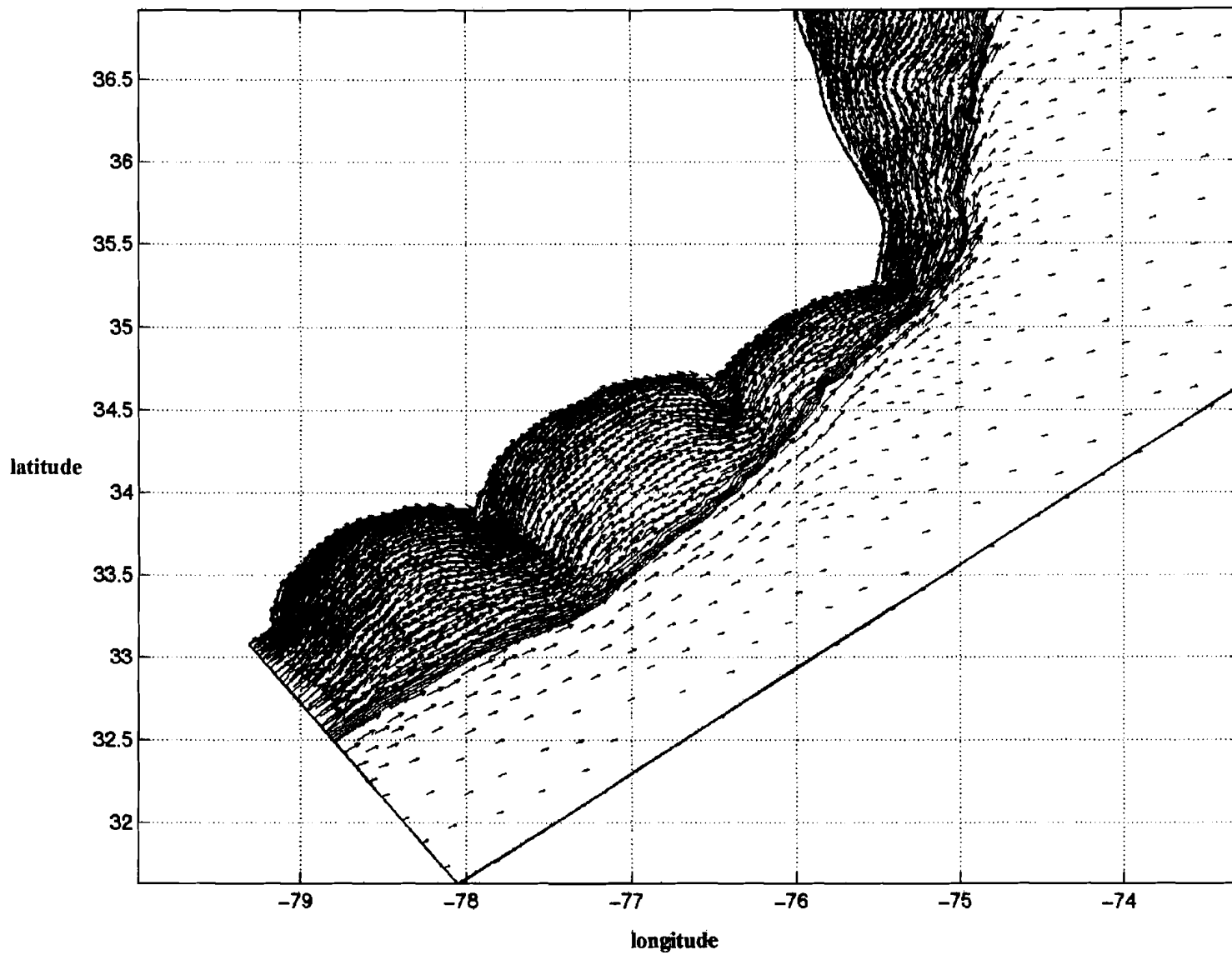


Figure 14. Model surface response to average August conditions

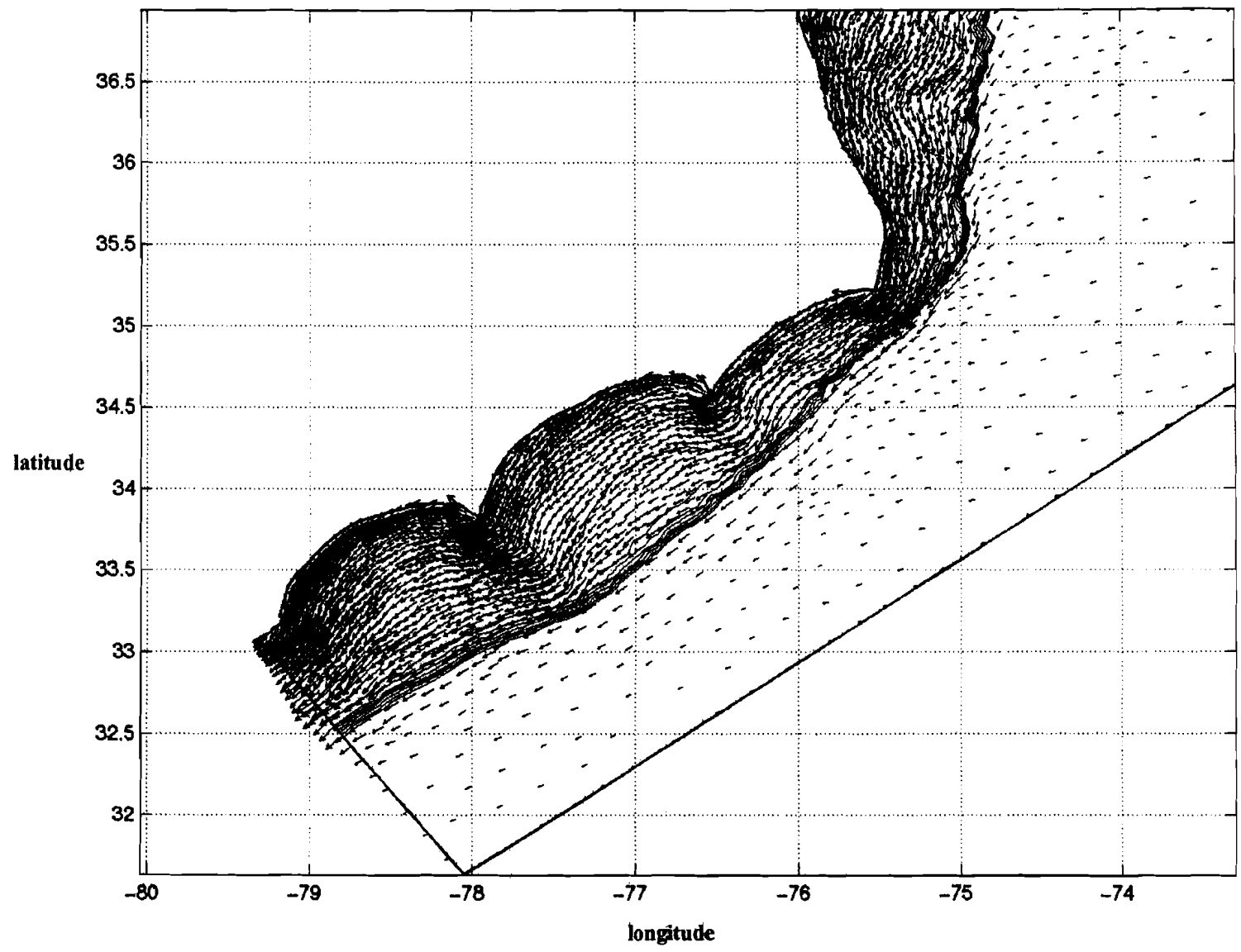


Figure 15. Model surface response to average September conditions.

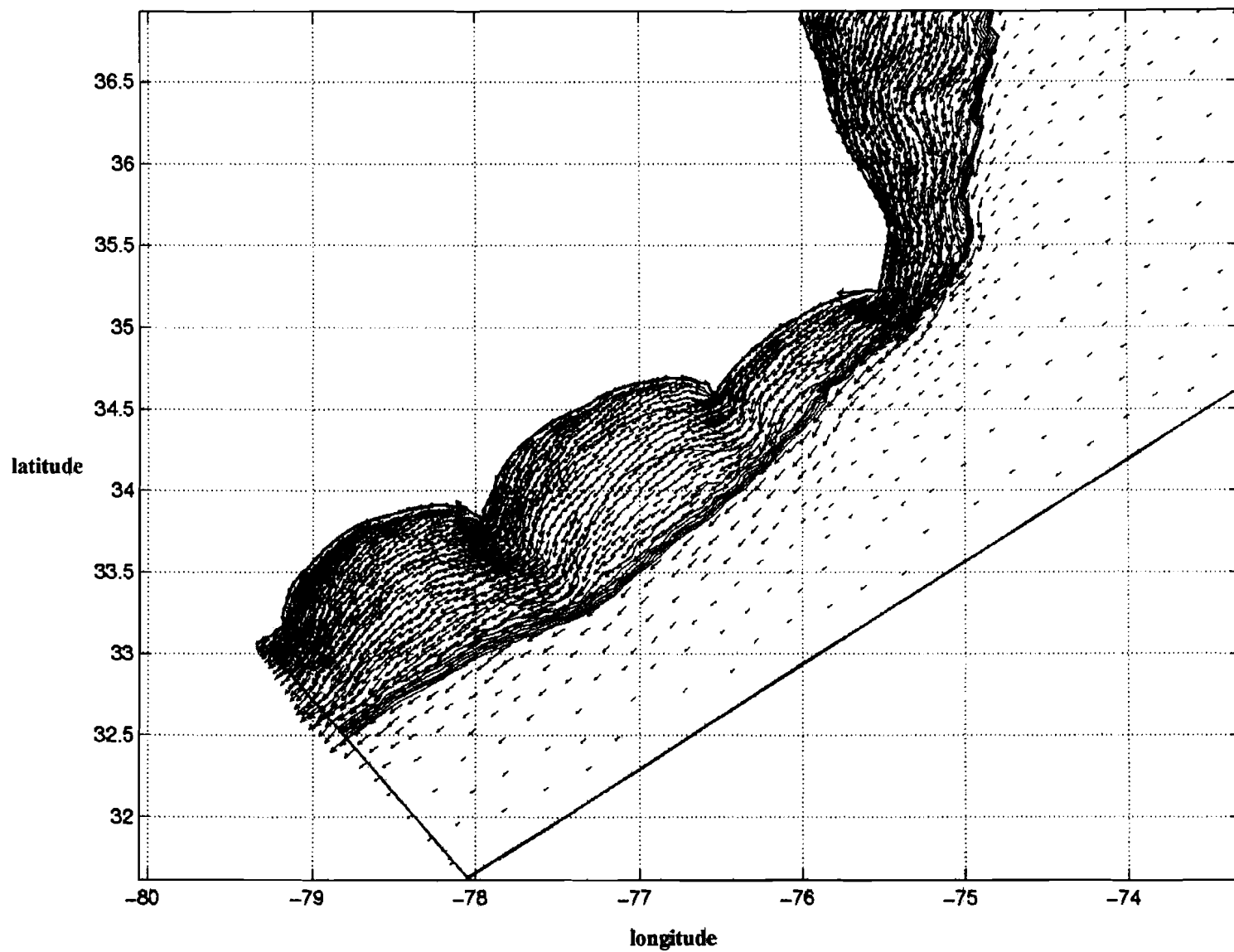


Figure 16. Model surface response to average October conditions.

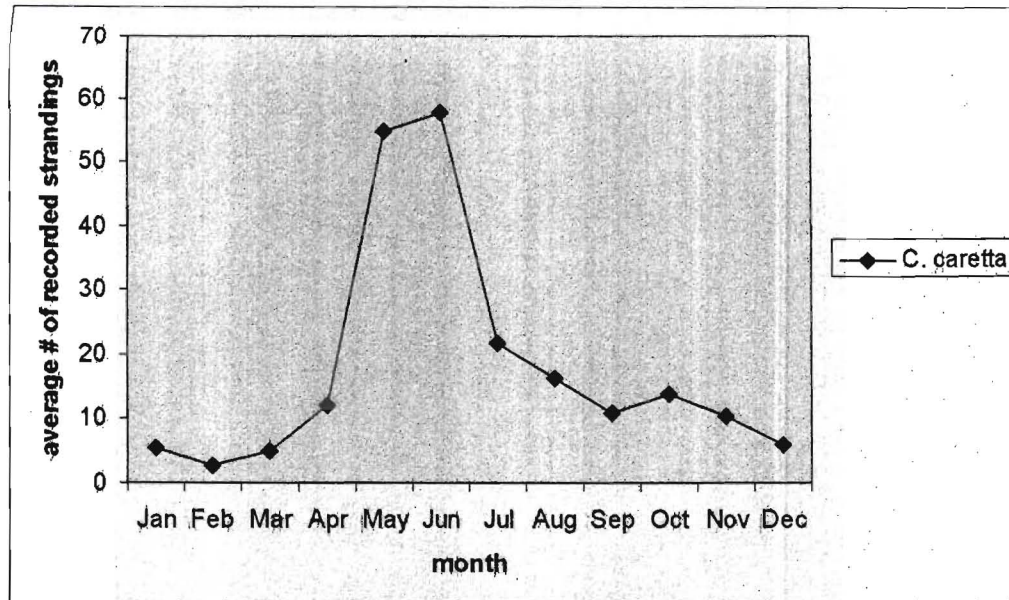


Figure 17. Five-year average ocean-beach strandings by *C. caretta* in North Carolina, sorted by month (1995-99).

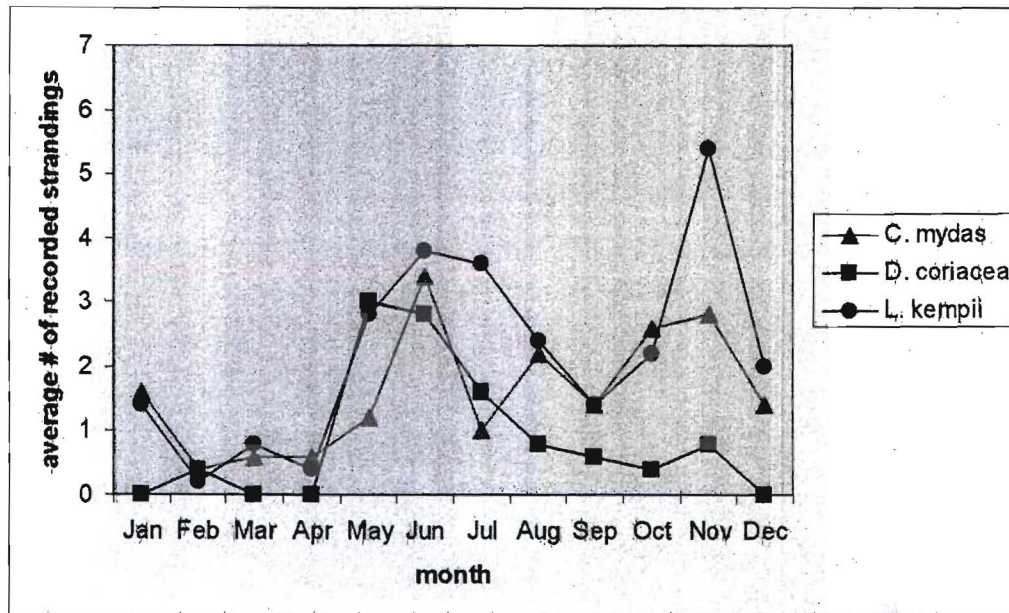


Figure 18. Five-year average ocean-beach strandings by *Chelonia mydas*, *Dermochelys coriacea*, and *L. kempii* in North Carolina, sorted by month (1995-99).

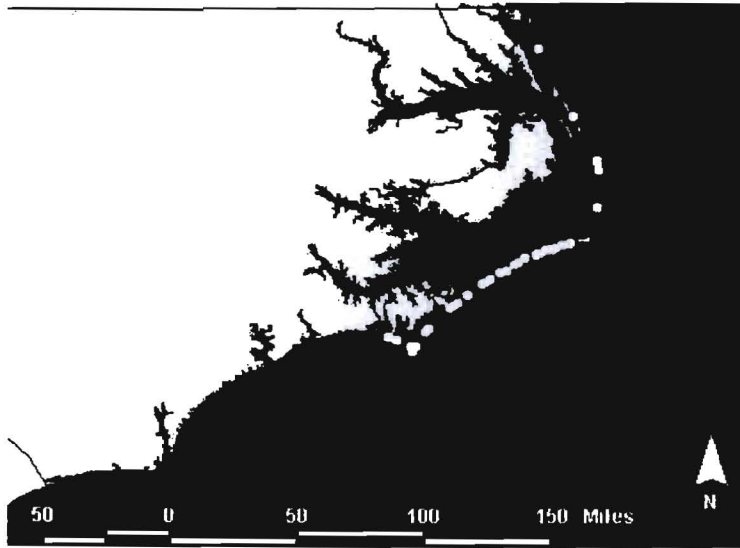


Figure 19. Point locations of ocean-beach turtle strandings (n = 43) recorded in January (1995-99).

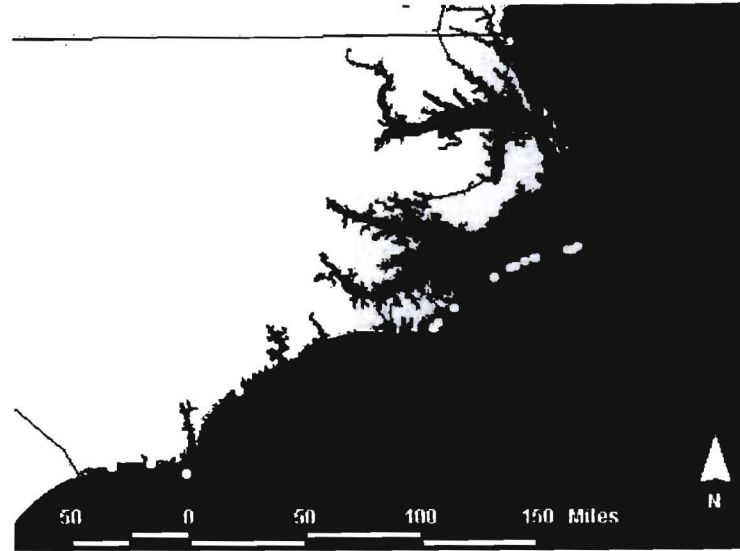


Figure 20. Point locations of ocean-beach turtle strandings (n = 17) recorded in February (1995-99).

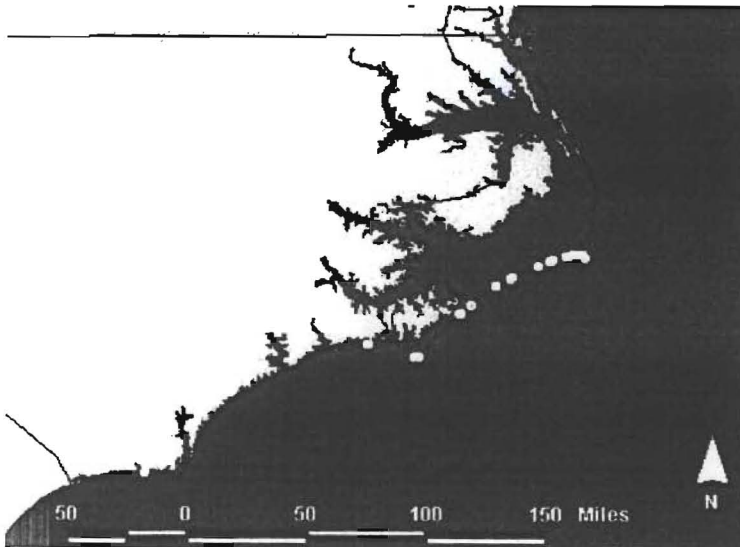


Figure 21. Point locations of ocean-beach turtle strandings (n = 32) recorded in March (1995-99).

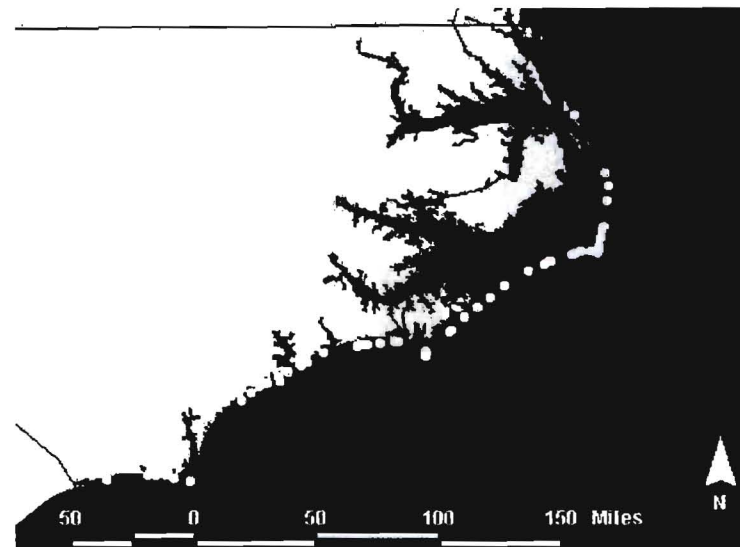


Figure 22. Point locations of ocean-beach turtle strandings (n = 65) recorded in April (1995-99).

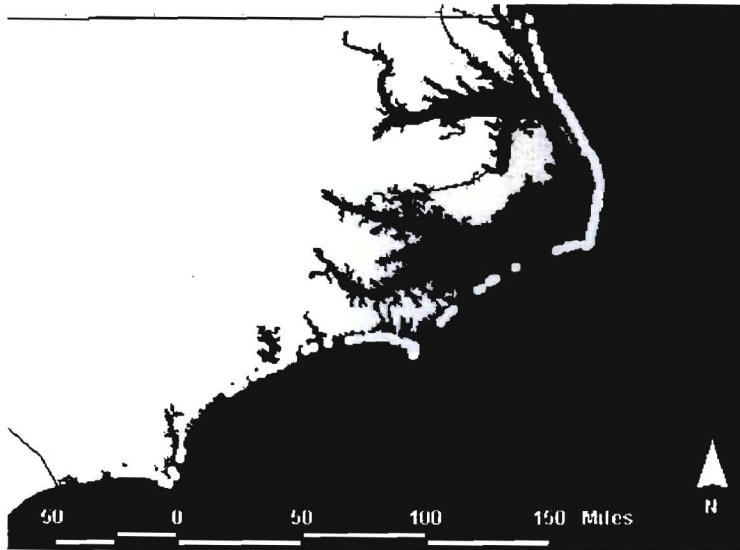


Figure 23. Point locations of ocean-beach turtle strandings (n = 310) recorded in May (1995-99).

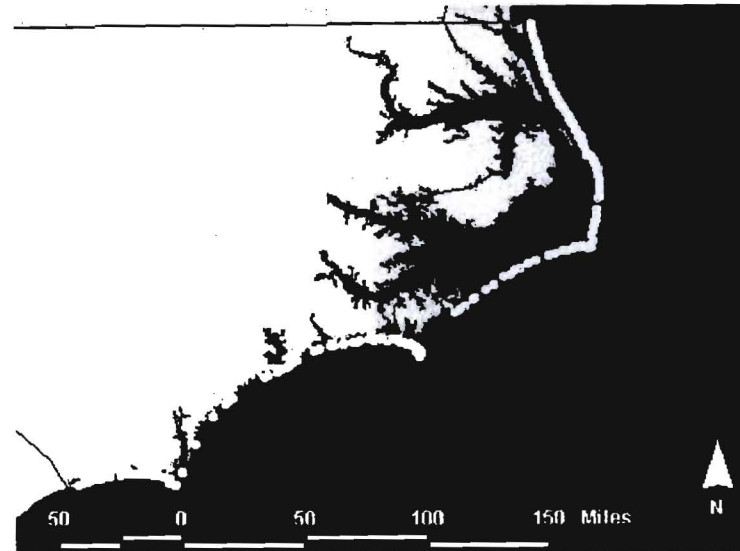


Figure 24. Point locations of ocean-beach turtle strandings (n = 340) recorded in June (1995-99).

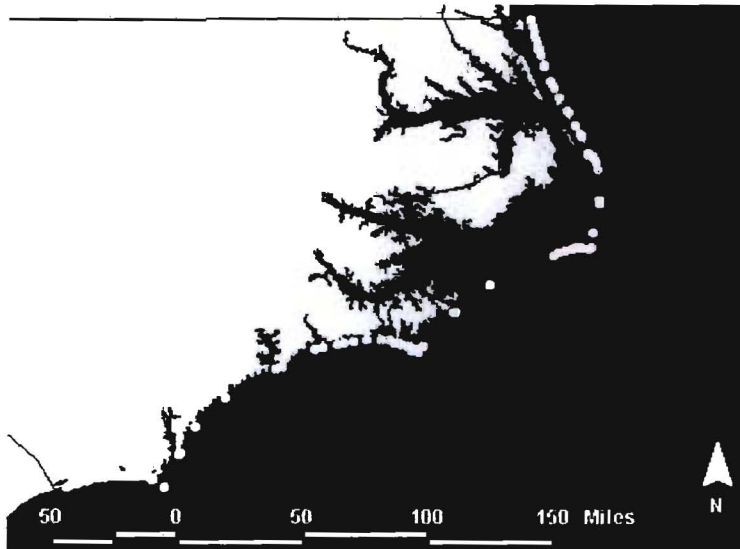


Figure 25. Point locations of ocean-beach turtle strandings (n = 141) recorded in July (1995-99).

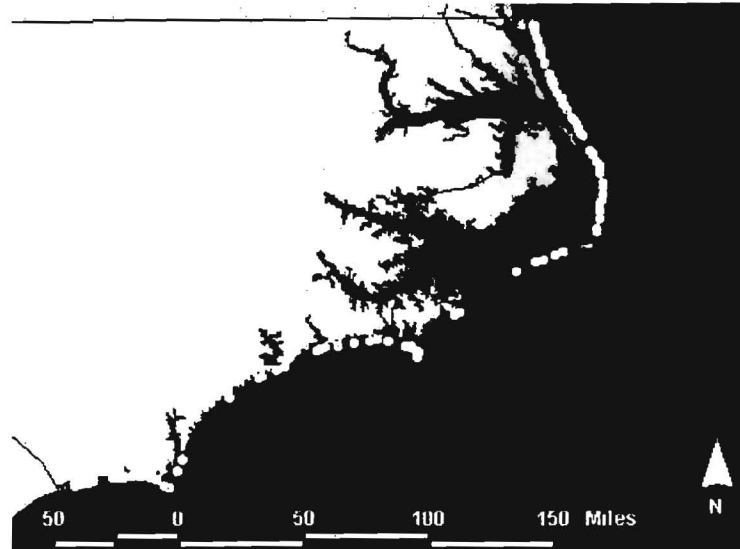


Figure 26. Point locations of ocean-beach turtle strandings (n = 110) recorded in August (1995-99).

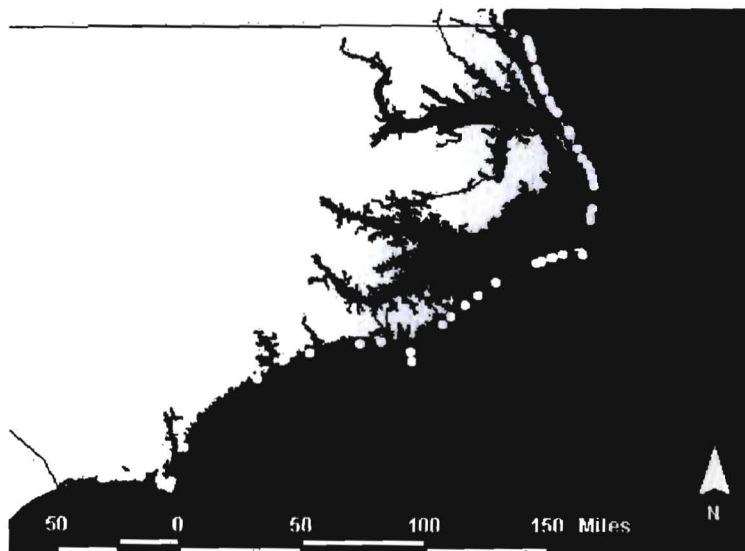


Figure 27. Point locations of ocean-beach turtle strandings (n = 70) recorded in September (1995-99).

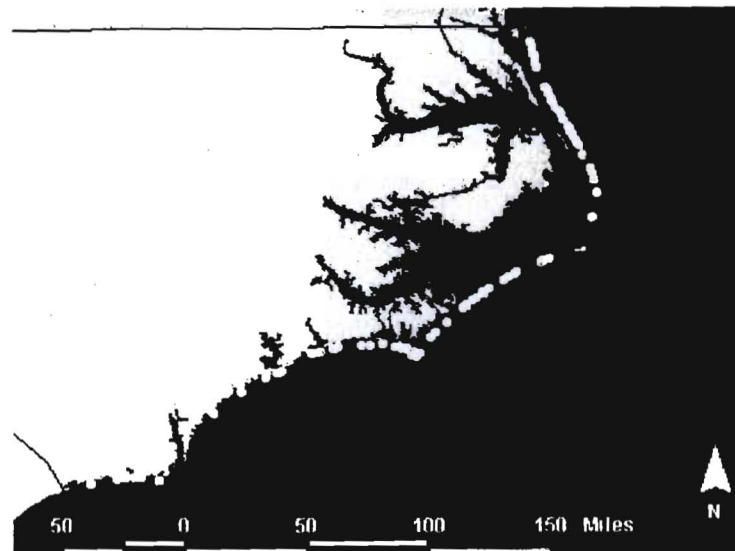


Figure 28. Point locations of ocean-beach turtle strandings (n = 96) recorded in October (1995-99).

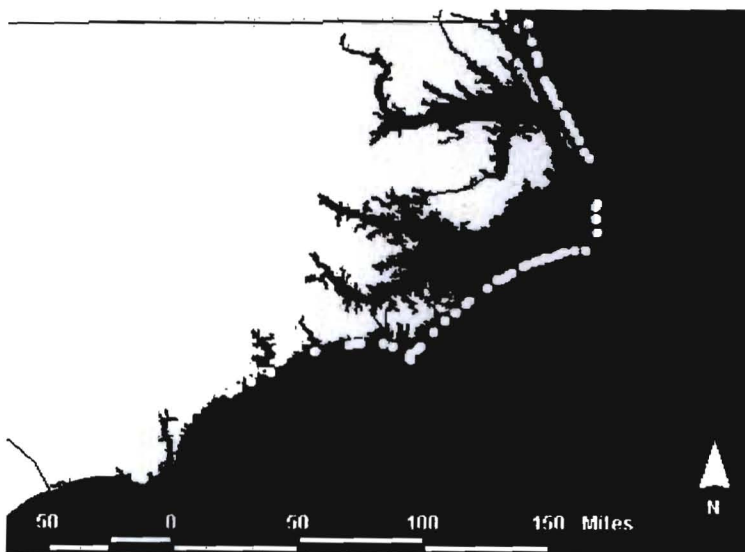


Figure 29. Point locations of ocean-beach turtle strandings (n = 96) recorded in November (1995-99).

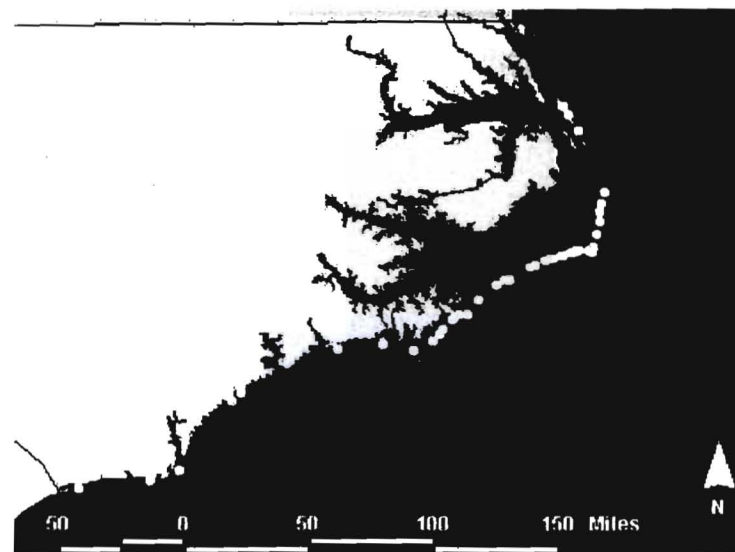


Figure 30. Point locations of ocean-beach turtle strandings (n = 45) recorded in December (1995-99).

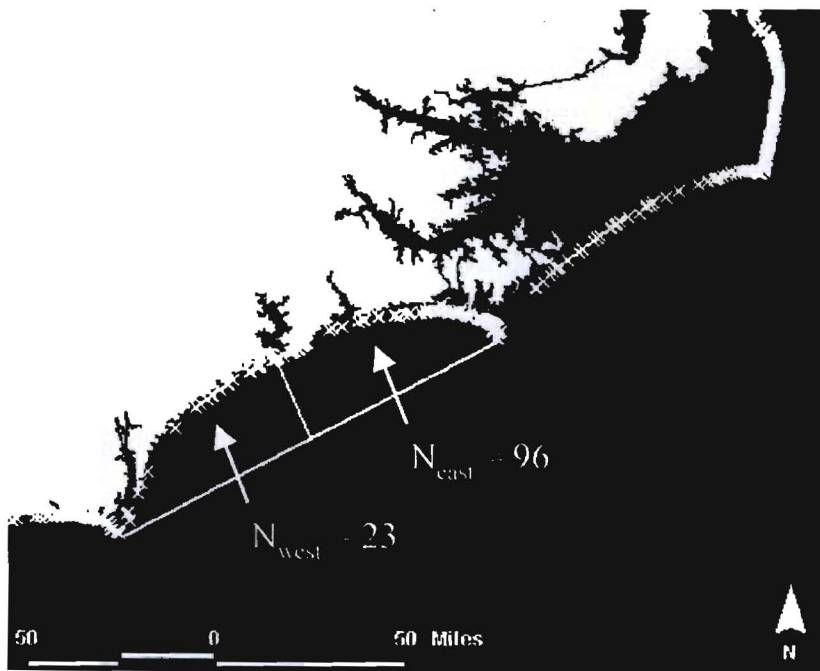


Figure 31. Combined turtle strandings inside Onslow Bay for May and June (1995-99).

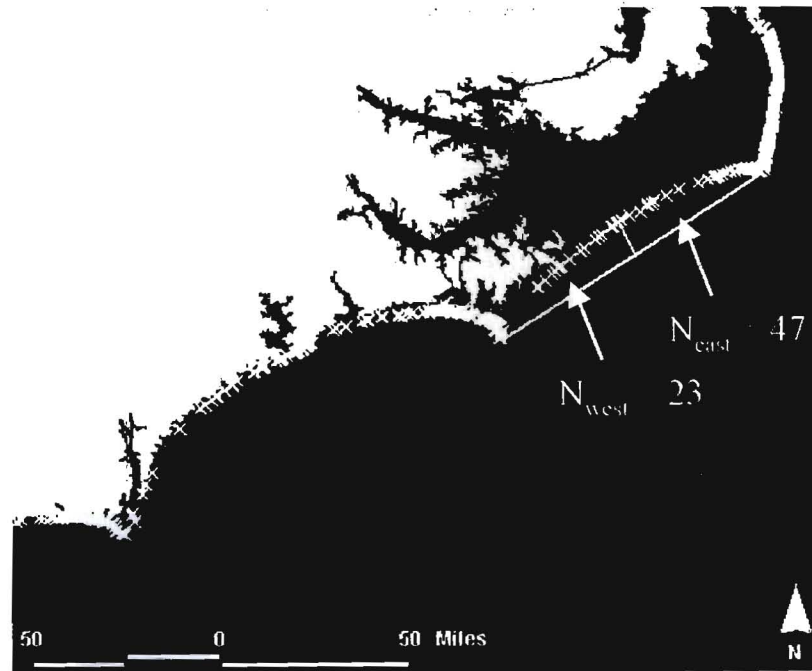


Figure 32. Combined turtle strandings inside Raleigh Bay for May and June (1995-99).

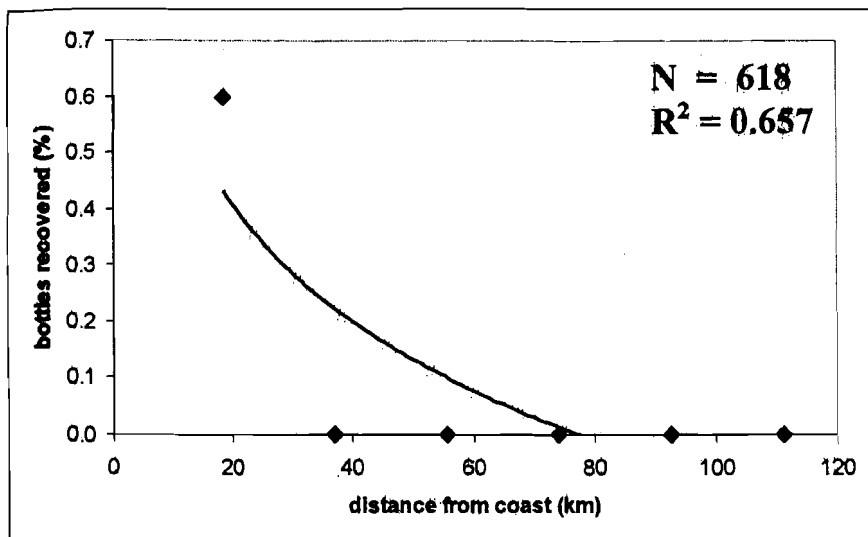


Figure 33. Recovery of surface drift-bottles released during January 1964 inside the Chesapeake Bight (derived from Harrison et al. 1967).

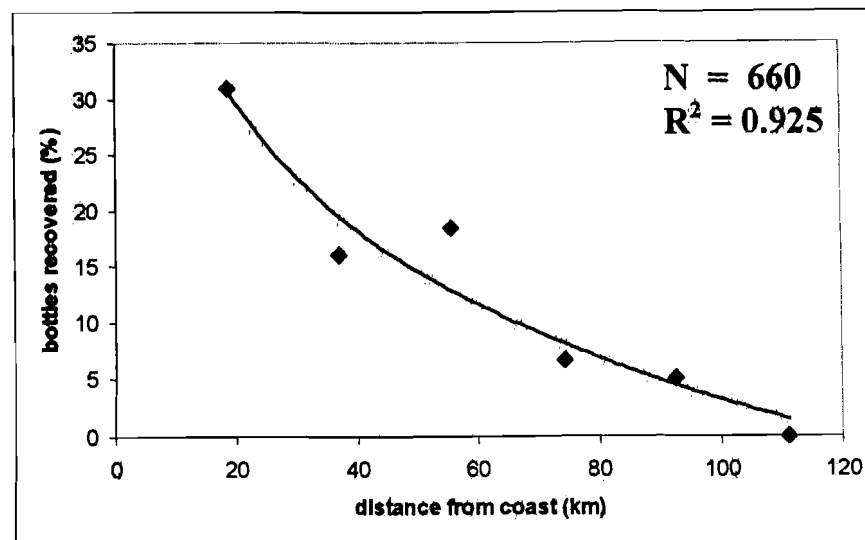


Figure 34. Recovery of surface drift-bottles released during April 1964 inside the Chesapeake Bight (derived from Harrison et al. 1967).

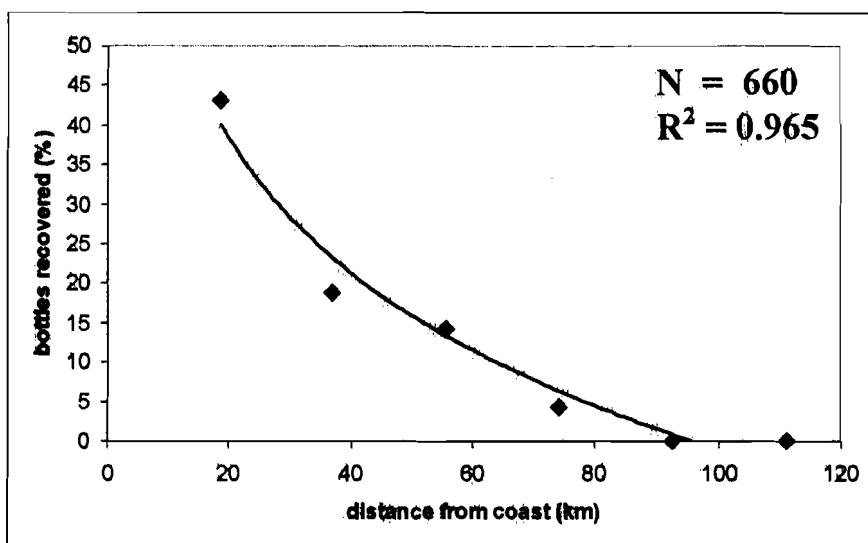


Figure 35. Recovery of surface drift-bottles released during June 1964 inside the Chesapeake Bight (derived from Harrison et al. 1967).

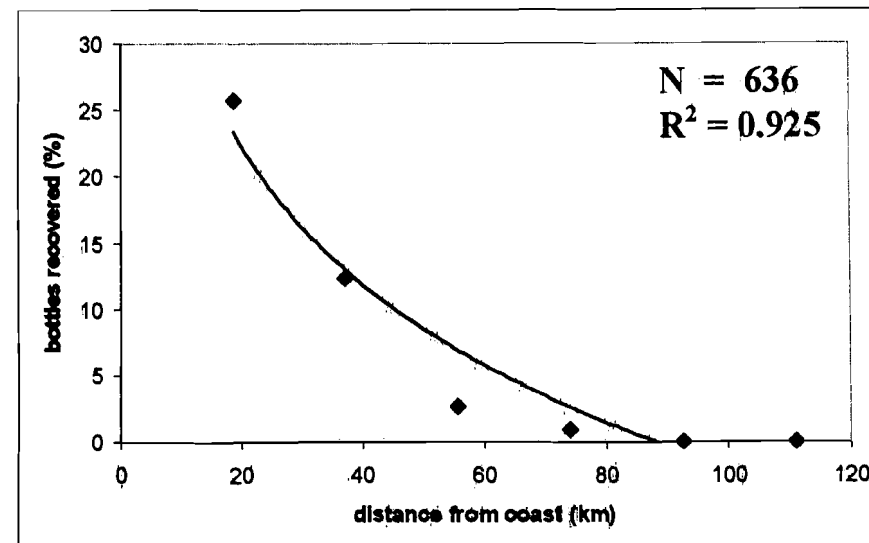


Figure 36. Recovery of surface drift-bottles released during October 1963 inside the Chesapeake Bight (derived from Harrison et al. 1967).

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