

**Lagrangian Flow Patterns north of Cape Hatteras using Near-Surface Drifters**

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## **Abstract**

Lagrangian flow patterns north of Cape Hatteras are examined using surface drifters initially deployed around Georges Bank. The drifters predominantly flowed southwestward over the continental shelf and slope. North of Cape Hatteras, the drifters become entrained in the Gulf Stream and are carried eastward into the central Atlantic Ocean. There are two types of entrainment. The first is characterized by a rapid change in direction and acceleration to the east. The radius of curvature is small as the drifters are entrained. The second type is characterized by a gradual change in direction with little or no acceleration. The radius of curvature is large (50-100 km) as the drifters are entrained. Drifters are carried from the shelfbreak front/slopewater gyre system into the Gulf Stream flow over a significant distance north of Cape Hatteras, with entrainment commonly occurring as far north as 38 degrees, 200 km north of Cape Hatteras. Only two drifters remained on the continental shelf and passed across Diamond Shoals into the South Atlantic Bight. In both cases, winds were southward (downwelling favorable) for the time period in which the drifters were between the mouth of Chesapeake Bay and Diamond Shoals. A number of drifters were also ejected from the Gulf Stream to the north and ended up recirculating over the slope on a time scale of several months. These results suggest that there are a variety of processes which determine the maximum southward penetration before entrainment into the Gulf Stream as well as the speed of the cross-slope entrainment.

## **Introduction**

Gabriel Csanady contributed a number of important papers on the structure of the slope gyre in the Middle Atlantic Bight as well as the processes contributing to shelf/slope exchange. His leadership on a number of important experiments substantially contributed to our present day understanding of the slope gyre and its complex interactions with both the Gulf Stream and the flow over the continental shelf.

Two of the most significant papers which focused attention on the slope gyre and provided important theory devoted to slope flows were Csanady and Hamilton (1988) and Csanady (1988). Csanady and Hamilton (1988) defined the slope water gyre system and characterized the flow structure and transports. This was a significant paper because it emphasized the continuity of the slope water gyre and clearly defined the structure of the sea surface height field associated with the gyre. Csanady (1988) summarized the observational understanding of the slope water gyre and applied his dynamical insight into the implications of the ambient potential gradient

associated with the topography and its impact on the structure of the slope flow. Our conceptual picture of the slope water gyre has largely been determined by these two papers.

A significant scientific problem is the manner in which the slope water gyre interacts with the Gulf Stream and continental shelf. It has long been recognized (Ford et al., 1952; Fisher, 1972) that the flow over the continental shelf in the Middle Atlantic Bight does not extend into the South Atlantic Bight and that the Gulf Stream entrains the vast majority of the shelf water (the "Ford water"). More recently, Lillibridge et al. (1990) carried out a high-resolution survey of the entrained shelf water and documented the subduction of the shelf water mass within the Gulf Stream and inferred mixing between the shelf water and the ambient Gulf Stream water.

Despite our knowledge of the large scale structure of the slope water gyre and the fate of the Middle Atlantic Bight shelf water, however, the details of the offshore flows of both shelf and slope water which become entrained are not well understood. Churchill and Cornillon (1991) described the complex interaction of Gulf Stream, slope, and shelf water over the upper slope north of Cape Hatteras. They also used remotely sensed sea surface temperature distributions to relate ephemeral surface fronts to near-surface geostrophic offshore flows. Churchill et al. (1993) also examined the potential for mixing between Gulf Stream and slope waters.

In order to clarify the details of entrainment of shelf and slope waters into the Gulf Stream near Cape Hatteras, we will use surface drifters to examine the Lagrangian flow patterns. The drifters were initially launched around Georges Bank as part of the GLOBEC (Global Ecosystems) Northwest Atlantic program and have been studied to examine flow around Georges Bank (Brink et al., 2004) and within the shelfbreak front (Lozier and Gawarkiewicz, 2001).

The following sections describe the data set and processing (Section 2), analysis of four typical trajectories illustrating entrainment (Section 3), and special cases including shelf flow past Cape Hatteras and recirculation from the Gulf Stream into the slope gyre (Section 4). The discussion of the results focuses on the cross-shelf Ekman transport for the two drifters which passed south of Cape Hatteras and the meridional distribution of the cross-shelf flow (section 5). Results are summarized in section 6.

## **Drifter Methodology and Data Processing**

The drifters we use for this study were deployed by the GLOBEC Northwest Atlantic Program by R. Limeburner, who kindly provided the data set which was processed and quality controlled. A general description of the drifter deployments, trajectories, and data processing are found in Limeburner et al. (2000), while an analysis of the Lagrangian fields around Georges Bank appears in Brink et al. (2004). A brief summary of the drifter methodology is provided here.

The drifters were deployed around Georges Bank and the area north of the Great South Channel from 1995-1999. Two hundred and three drifters were launched and were drogued to 10 m depth. The drifters contained an ARGOS satellite transmitter and fixes were generally obtained six times per day. The satellite fixes were interpolated to six-hourly positions using cubic splines, and then low-pass filtered using the PL66 filter which has a half-power point at 38 hours. Trajectories also were examined to remove erratic fixes. In addition to the position and velocity data, sensors for temperature and submergence (transmitter below water) were also included. While there were numerous failures in the temperature sensors, many of the drifters which passed into our study area did obtain reasonable temperature data which we will use.

The primary area we will consider is bounded by 35 to 38 Degrees North in Latitude and 72 to 76 Degrees West in longitude. A surprisingly large number of drifters, 63, passed through this domain despite being launched well north over or near Georges Bank. This enables us to crudely consider the Lagrangian flow characteristics north of Cape Hatteras, but does not allow us to compute typical statistics such as particle-pair dispersion and eddy diffusivities. Instead, we will focus on presenting trajectories which are representative of a number of other drifters and analyze the characteristics of these trajectories and their relation to surface thermal fronts and wind forcing. Winds used in the analysis were obtained from the National Buoy Data Center buoy 44014. This meteorological buoy is located at 36.61 Degrees N, 74.84 Degrees W, in 47 m of water.

The entire ensemble of drifter trajectories appears in Figure 1. The following are a few general comments on the trajectories. The majority of the drifters entered the northern boundary of our arbitrary study area, although a few entered from the eastern boundary. The majority of the drifters entered the domain over the continental slope. None of the drifters passed across the Gulf Stream over deep water, but two drifters continued on the continental shelf around Diamond Shoals and into the South Atlantic Bight. In the next two sections, we will examine typical trajectories which demonstrate entrainment into the Gulf Stream and then examine special cases, flow into the South Atlantic Bight around Diamond Shoals and also drifters which recirculate within the slope gyre.

### **Typical trajectories and their relation to wind forcing and surface thermal features**

Nearly all of the trajectories depart the study domain through the eastern boundary, with only a single drifter passing through the southern boundary. The drifters typically pass southward through the northern boundary and become entrained in the Gulf Stream. After examining all 63 trajectories, we have determined that there are two primary types of entrainment. The first is marked by a very abrupt turn to the northeast and rapid acceleration. The second type is marked by a very gradual turn to the northeast and a much lower rate of acceleration. In addition to the difference in the characteristics of the turning, we found that the latitudinal range over which these two types of entrainment occurred was large, with entrainment frequently occurring as far north as 38 Degrees North (determining the boundaries of our study area). We will now present four trajectories that we regard as typical of the two types of entrainment. The broad turning entrainment is common in the northern portion of the study domain (north of 36 Degrees N). South of 36 Degrees N, the entrainment is always abrupt, but is more complicated when drifters are located over the shelf as they approach Cape Hatteras. We will present two southern trajectories, one passing over the continental slope and one over the continental shelf.

First, let us consider an example of gradual entrainment in the northern region (Figure 2). In this case, the drifter is passing southwestward along the northern edge of the domain. At 37.3 Degrees North, the drifter turns offshore. The initial position would suggest that the drifter is in the vicinity of the shelfbreak front, with speeds comparable to a climatological mean geostrophic

flow (20-30 cm/s; Linder and Gawarkiewicz (1998) show mean geostrophic velocities of up to 25 cm/s in their bimonthly climatology in this region). Initially, the temperature measured by the drifter is as low as 12 Degrees C.

After turning to the southeast, the temperature increases to 20 Degrees C but the speed remains within a range of 20 to 30 Degrees C. Near 36.5 Degrees North, the drifter turns to the east and accelerates to 70 cm/s. The temperature, however, actually decreases to 17 Degrees C, suggesting that the drifter has not become entrained in the warmest Gulf Stream water mass. The turning radius for this case is approximately 100 km, and the drifter took 6.25 days to cross the slope gyre between the shelfbreak front and entrainment into the Gulf Stream.

The second type of entrainment, involving an abrupt turn, is significantly different in character (Figure 3). For this trajectory, the drifter again begins near the shelfbreak moving southward at approximately 40 cm/s. However, the drifter takes an abrupt northeastward turn at 36.3 Degrees North. The drifter accelerates fairly rapidly, reaching a speed of 100 cm/s near 73 Degrees W. In this case, the drifter decelerates from 40 to 5 cm/s before moving off rapidly to the northeast, suggesting that it might have been near a stagnation point between the shelfbreak front and Gulf Stream before becoming entrained in the Gulf Stream. The temperatures vary along the northeastward portion of the trajectory, but are as high as 25.5 Degrees C, suggesting that the drifter passed through Gulf Stream water masses. In general, the surface temperatures are much higher in this trajectory because of the season (summer). In this case, the radius of curvature is roughly 20 km.

The entrainment in the southern portion of the domain can be quite dramatic (Figure 4). This drifter moved southward along the 100 m isobath until turning abruptly at 35.1 Degrees N. The drifter temperature went from 14 to 22 Degrees C over an alongslope distance of 20 km. The drifter rapidly accelerated from 20 to 100 cm/s over a horizontal distance of 40 km. The drifter temperatures were over 22 Degrees C, consistent with passage through a Gulf Stream water mass in winter. The turning radius was 5 km.

A second example of abrupt entrainment in the southern portion of the domain is more complicated (Figure 5). This drifter passed along the middle of the continental shelf at approximately the 30 m isobath. Near 35.75 Degrees N, the drifter was carried offshore 20 km before turning southward, presumably in the flow associated with the shelfbreak front. At 35.1 Degrees N, the drifter turned abruptly to the northeast, accelerating rapidly from 10 to 100 cm/s. In contrast to the previous drifter, the temperature remained fairly constant in the region of abrupt entrainment, at around 22 Degrees C. The temperature increased to 25 Degrees C at 73.5 Degrees W. This trajectory was in the summer, which explains the lack of strong thermal gradients at 10 m depth.

Let us now consider the impact of wind forcing on the trajectories. For the first case (Figure 6a), a broad turning for entrainment in the north, wind forcing appears to play an important role in the initial cross-shelf motion. As the drifter travels between 37.5 and 37 Degrees N, the winds blew from the south, giving rise to an eastward component to the Ekman transport. South of 37 Degrees N, however, the winds shifted to blowing from the southwest and also weakened substantially. The drifter continued at roughly the same speed and direction even after the wind decreased. The lower half of the southeastward portion of the trajectory appears to be associated with a thermal front (Figure 6b). Thermal (and density) fronts frequently cross the slope topography in this region, as previously documented by Churchill and Cornillon (1993). In this case, the initial departure from the predominantly along-isobath flow appears to have been initiated by the wind forcing and then continued in a presumably geostrophic cross-isobath flow.

For the second case, abrupt entrainment in the north, the wind forcing does not appear to play a significant role (Figure 7a). There is no significant wind forcing as the drifter moves along the upper slope. During the abrupt turn to the northeast, the Ekman transport was to the west, the opposite direction that the drifter was travelling. The surface thermal front associated with the Gulf Stream was located very close to the position at which the abrupt change in direction occurred (Figure 7b).

For the two southern cases of abrupt entrainment, the wind does not play an important role. For the third case (Figure 8a), the Ekman transport was to the west as the drifter abruptly turned to

the northeast. Cloud cover limited our choice of thermal images, but an image from several days before entrainment shows that the Gulf Stream thermal front was in close proximity to the position of the drifter's abrupt change in direction (Figure 8b). For the fourth case, in which the drifter travelled over the shelf before shifting position to the shelfbreak and then abruptly entraining, the winds did not appear to play a role. Ekman transport during the first cross-shelf shift in position, from the 30 m isobath to the shelfbreak, occurred as the winds blew from the north giving a westward Ekman transport (Figure 9a). Similarly, during the abrupt entrainment into the Gulf Stream, winds were from the northeast. Again, the Ekman transport opposed the direction of the drifter path. The Gulf Stream surface thermal front was again in close proximity to the point of abrupt entrainment (Figure 9b).

As drifters pass to the south, there is a substantial shift in the zonal distribution of the trajectories as they cross lines of constant latitude. In the north (Figure 10a), the drifters are fairly evenly distributed zonally. However, as drifters become entrained in the Gulf Stream and move to the northeast, the zonal distribution of the southward passing drifters is concentrated between 74 and 75.5 Degrees W, with no drifters east of 74 Degrees W (Figure 10b). This is consistent with the blank areas in the map in Figure 1 depicting all the drifter trajectories.

Examination of the trajectories shows that a majority of the entrainment events can be categorized as abrupt events (24 out of 41). The remaining 17 can be classified as gradual. The other trajectories either were limited to the extreme eastern portion of the study domain or were rotating within eddy features.

### **Two Special Cases- Passage into the South Atlantic Bight and Recirculation**

The fate of the vast majority of the drifters (61 of 63) was to become entrained into the Gulf Stream and depart the study domain moving eastward. We will examine the two drifter trajectories which did pass across Diamond Shoals into the South Atlantic Bight. We will also examine two drifter trajectories in which the drifters recirculated into the domain from the northward boundary after being ejected from the Gulf Stream.



One drifter which passed south of Diamond Shoals became entrained in the Gulf Stream (Figure 11a). Unfortunately, the thermistor on this drifter malfunctioned before reaching this region and the transmitter only worked intermittently so that the time intervals for speed estimates are long and irregular. This drifter penetrated as far south as 34.56 Degrees N before becoming entrained into the Gulf Stream. The most likely reason for the southward penetration is an extended time period of southward blowing winds (Figure 11b). Pietrefesa et al. (1994) found that Middle Atlantic Bight shelf water (and Virginia Coastal Water) was normally found during times of southward blowing winds driving onshore Ekman transport. They showed that these downwelling flows accelerated the coastal current and allowed it to penetrate further south across Diamond Shoals. The drifter took 3.25 days to pass between 35.92 Degrees N and 34.6 Degrees N, for an average speed of 52 cm/s. After becoming entrained in the Gulf Stream, the drifter was in close proximity to the surface thermal front associated with the Gulf Stream (Figure 11c). Thus, in this case, the drifter enters the South Atlantic Bight but only penetrates 50 km south of Diamond Shoals.

The second drifter penetrated a large distance south of Cape Hatteras (Figure 12a). This drifter stopped transmitting when it was at a latitude of 33.74 Degrees N, 140 km south of Cape Hatteras. The drifter moved between 36 and 35 Degrees N in 1.75 days, for an average speed of 77 cm/s. The maximum velocity (over a six hour time interval) was 87 cm/s. For this case, southward blowing winds were present during this time (Figure 12b). It is interesting to note that in this case there are no sharp thermal fronts over the shelf in contrast to other trajectories (Figure 4). There is a fairly uniform surface temperature of about 15 Degrees C. This would imply that Middle Atlantic Bight shelf water penetrated into the South Atlantic Bight. Churchill and Berger (1998) identified the Hatteras Front as the southern boundary of the Middle Atlantic Bight shelf water. The lack of thermal gradients in this trajectory would imply that the front was south of Hatteras, a situation also described in Savidge (2002). Unfortunately, clouds obscured the satellite thermal imagery as the drifter passed around Cape Hatteras. An image taken a week prior to the passage suggests that the Gulf Stream might have had a southern deflection at 76 Degrees W (Figure 12c).

Another unusual class of trajectories included drifters which passed through the domain more than once as they recirculated within the slope gyre. A nice example of this appears in Figure 13. After ejection from the Gulf Stream at 68 Degrees W, the drifter passes northward across the slope gyre and returns to the Hatteras region, where it is entrained a second time. It is interesting to note that one of the entrainment events is of the abrupt type and one is of the gradual type described in the previous section. The drifter returned to 38 Degrees N after 41 days. Two other studies have also documented rapid transport from the Gulf Stream to the edge of the continental shelf on fairly rapid time scales (Hare et al., 2003; Rasmussen et al., 2005). As Hare has discussed, cross-slope flow may be significant for transport of larval fish between the South Atlantic Bight and estuaries of the Middle Atlantic Bight.

A second example of recirculation through the slope gyre is much more complicated (Figure 14). In this case, the drifter appears to have moved in and out of various slope water eddies and traversed a number of shelf and slope water masses. The time interval between crossings of 38 Degrees N was significantly larger than the previous case, 106 days. Thus, there is a wide range of time scales for recirculation into the Hatteras domain across the slope gyre.

## **Discussion**

We will briefly discuss two separate issues; the role of wind forcing in transporting drifters across Diamond Shoals and the meridional distribution of offshore flow. The latter will be examined using a criterion developed by Lozier and Gawarkiewicz (2001), the point at which a trajectory crossed the 1000 m isobath.

The wind forcing appears to have played a significant role in the first drifter trajectory which extended into the Middle Atlantic Bight (Figure 11c). We can calculate the westward distance that the drifter would have been carried assuming a constant layer mixed depth. This is given by

$$L_x = \int \tau(t) / \rho f H dt,$$

where  $L_x$  is the eastward translation distance,  $\tau$  is the northward component of wind stress,  $f$  is the Coriolis parameter, and  $H$  is a constant mixed layer depth, which we will assume for this case is 40 m. During the time span over which the drifter passed between 36 Degrees N and 34.54 Degrees N,  $L_x = -22.4$  km (westward translation). The mean wind stress over this time interval (3.25 days) was  $-0.2669$  N/m<sup>2</sup>. The westward translation of the drifter over the same time interval was 71 km. Halving the mixed layer depth to 20 m would double the wind-driven westward translation to 45 km. Thus the wind driven flow does not explain all the westward motion, but the isobaths curve to the southwest south of Cape Hatteras. Buoyancy driven motion along the isobaths may account for some of the westward motion.

Surprisingly, the second drifter which passes south of Cape Hatteras has virtually no westward translation due to wind stress. During the 1.75 days this drifter (Figure 12c) passed between 36 and 35 Degrees N, the northward component of wind stress was  $-0.0992$  N/m<sup>2</sup>. The wind direction varied from 20 to 60 Degrees True (direction wind was blowing from) so that much of the stress was directed westward and not southward. The westward translation due to wind stress over this time period was only 4.3 km to the west. The wind does not appear to have played a significant role in restraining the drifter close to shore.

The spatial distribution of the drifter positions as they cross the 1000 m isobath appears in Figure 15a. The drifters cross this isobath over nearly the full range of the study area, from 35.16 Degrees N to 37.98 Degrees N. Twenty six of the 63 drifters passing through this area originated shoreward of the 1000 m isobath. Of these, only two passed across the 1000 m isobath south of 35.5 Degrees N. One of the two (Figure 11a) was entrained into the Gulf Stream south of Cape Hatteras. The crossing positions are more evenly distributed north of 35.5 Degrees N. However, the crossing points are surprisingly frequent in the northern portion of the region. A histogram of the latitudinal distribution of the crossing points (Figure 15b) shows that half of the 26 drifters cross the 1000 m isobath north of 37.4 Degrees N. South of 35.5 Degrees N there is a distinct decrease, and this probably marks a southern boundary for drifters which remain within the shelfbreak front. The drifters which crossed south of 35.5 degrees N were both located over mid-shelf, near the 30 m isobath, as they crossed 35.5 Degrees N. The overall mean in the latitudinal distribution was 36.87 Degrees N.

The distribution of crossing points is surprising in the sense that one might have expected a pronounced peak in the latitudinal distribution near the mean position of the Gulf Stream if the abrupt entrainment type dominated. The distribution suggests that the gradual type of entrainment is very important and may occur significantly northward of Cape Hatteras. Further work is clearly necessary to determine the underlying hydrographic structure over the slope during these northern gradual entrainment events, as well as a theoretical understanding of why the shelfbreak front should separate or fragment near these crossing points. The distribution also implies that the type of thermal front which crosses the continental slope observed by Churchill and Cornillon (1993) may be a fairly frequent event south of 38 Degrees N.

## **Summary**

Analysis of drifter trajectories over the shelf and slope north of Cape Hatteras indicates that there are two types of entrainment into the Gulf Stream, abrupt and gradual. The abrupt events are characterized by a sharp change in direction with a rapid acceleration, while the gradual events have a large radius of curvature and small accelerations. Two drifters over the shelf passed south of Cape Hatteras, and a slightly larger number (4 of 63) recirculated from the Gulf Stream back to the shelfbreak.

## **Acknowledgements**

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Discussions with Harvey Seim were also helpful. This work was supported under NSF Grant OCE-0327249.

## Figure Captions

Figure 1- A diagram containing all 63 trajectories of drifters passing within our study domain. All drifters were drogued to 10 m depth.

Figure 2- A drifter trajectory exhibiting a gradual entrainment into the Gulf Stream from the shelfbreak. Overplotted on the trajectory in the left panel is the temperature and on the right panel is the speed calculated from the six hourly low-pass filtered buoy positions. The drifter passed through the study domain between May 20 and June 1, 1999.

Figure 3- A drifter trajectory exhibiting an abrupt entrainment into the Gulf Stream in the northern area of the study domain. The drifter passed through the study domain between August 21 and September 3, 1996.

Figure 4- A drifter trajectory with abrupt entrainment into the Gulf Stream in the southern area of the study domain. The drifter passed through the study domain between November 14, 1998 and January 1, 1999. Note the large thermal gradients along the outer shelf near the entrainment region.

Figure 5- A drifter trajectory showing two entrainment events, first offshore into the shelfbreak frontal jet and then into the Gulf Stream. The drifter trajectory spanned September 21 to October 22, 1997.

Figure 6- a) The trajectory of the drifter shown in Figure 2 with winds from NDBC buoy 44009 overplotted as a function of time. b) The same trajectory overplotted on an image of sea surface temperature produced by the NOAA Coastwatch program. The position of the drifter when the image was taken is denoted by the large black dot.

Figure 7- a) Winds overplotted for the drifter trajectory shown in Figure 3. The sea surface temperature is overplotted in b).

Figure 8- a) Winds and b) sea surface temperature for the drifter trajectory shown in Figure 4.

Figure 9- a) Winds and b) sea surface temperature for the drifter trajectory shown in Figure 5.

Figure 10- The distribution of the longitude of drifters crossing a) 38 Degrees N and b) 36 Degrees N. Note that the distribution is much more evenly distributed in a), but is strongly concentrated in the west in b). This is consistent with the envelope of trajectories appearing in Figure 1.

Figure 11- The trajectory of a drifter which passed southward across Cape Hatteras. The trajectory is plotted in a), with winds overplotted in b) and sea surface temperature overplotted in c). The temperature probe failed on this drifter, and the position fixes were intermittent. The drifter passed through the domain between November 23 and December 23, 1996.

Figure 12- The trajectory of a second drifter which passed southward across Cape Hatteras. The temperature and speed are overplotted in a), the winds in b), and the sea surface temperature in c). The drifter passed through the domain between April 27 and June 8, 1997.

Figure 13- The trajectory of a drifter which recirculated across the slope region and returned to the shelfbreak area north of Cape Hatteras. Temperature is overplotted in the left panel and speed in the right panel.

Figure 14- The trajectory of a drifter with a much more complicated trajectory which recirculated to the shelfbreak.

Figure 15- a) The distribution of positions at which drifters moved offshore across the 1000 m isobath. B) A histogram of the crossing points distributed by latitude, showing a clear decrease in frequency with southward position.

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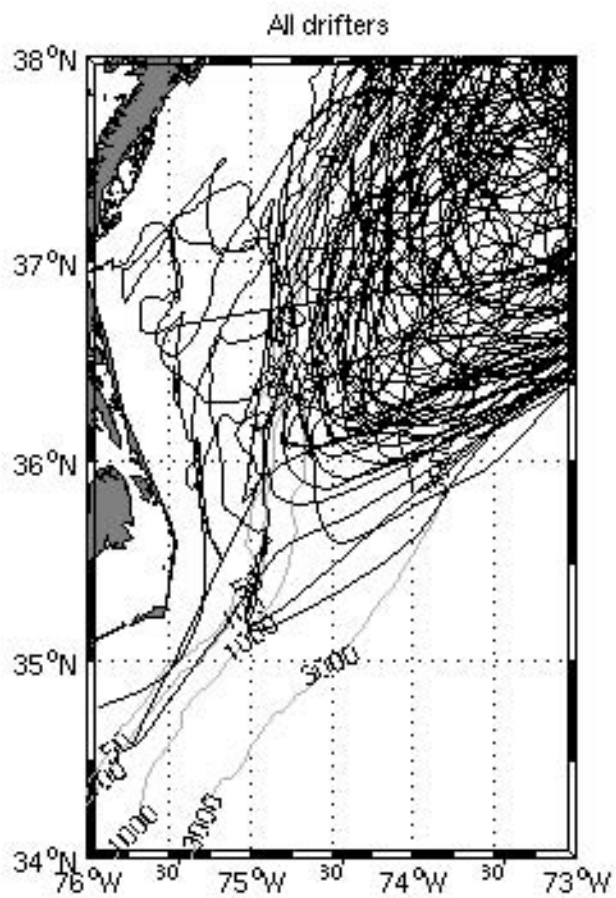


Figure 1

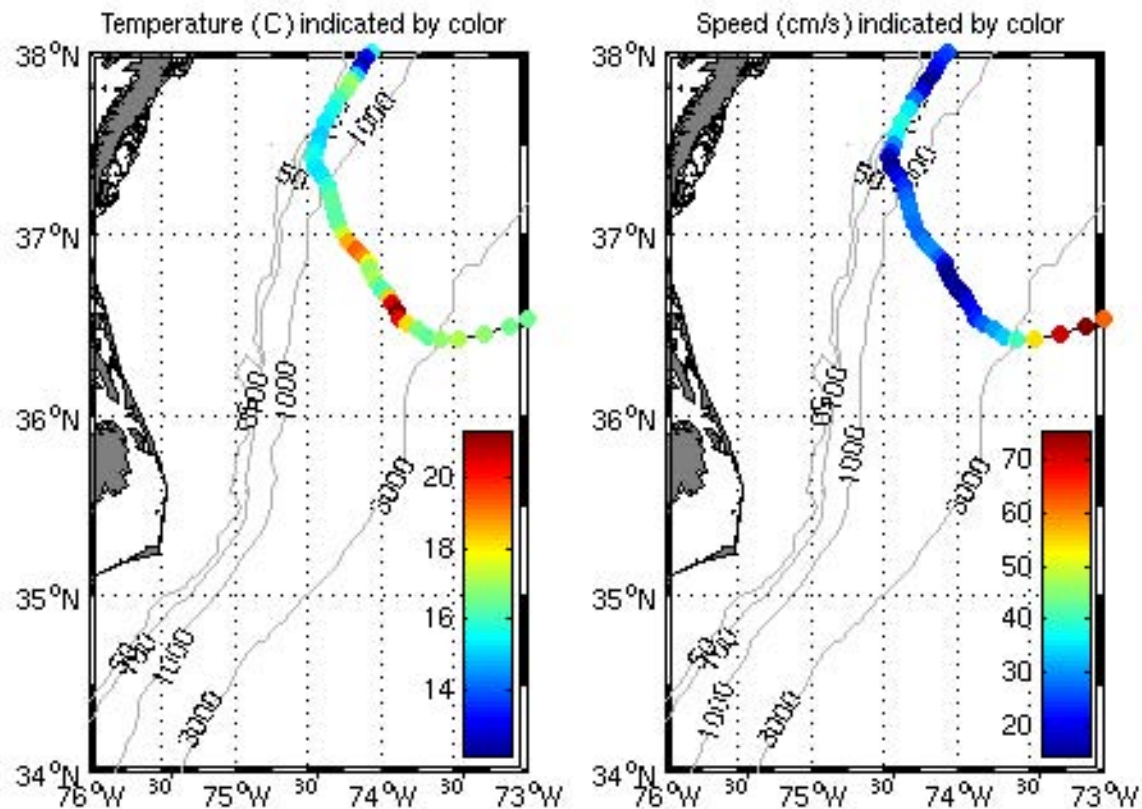


Figure 2

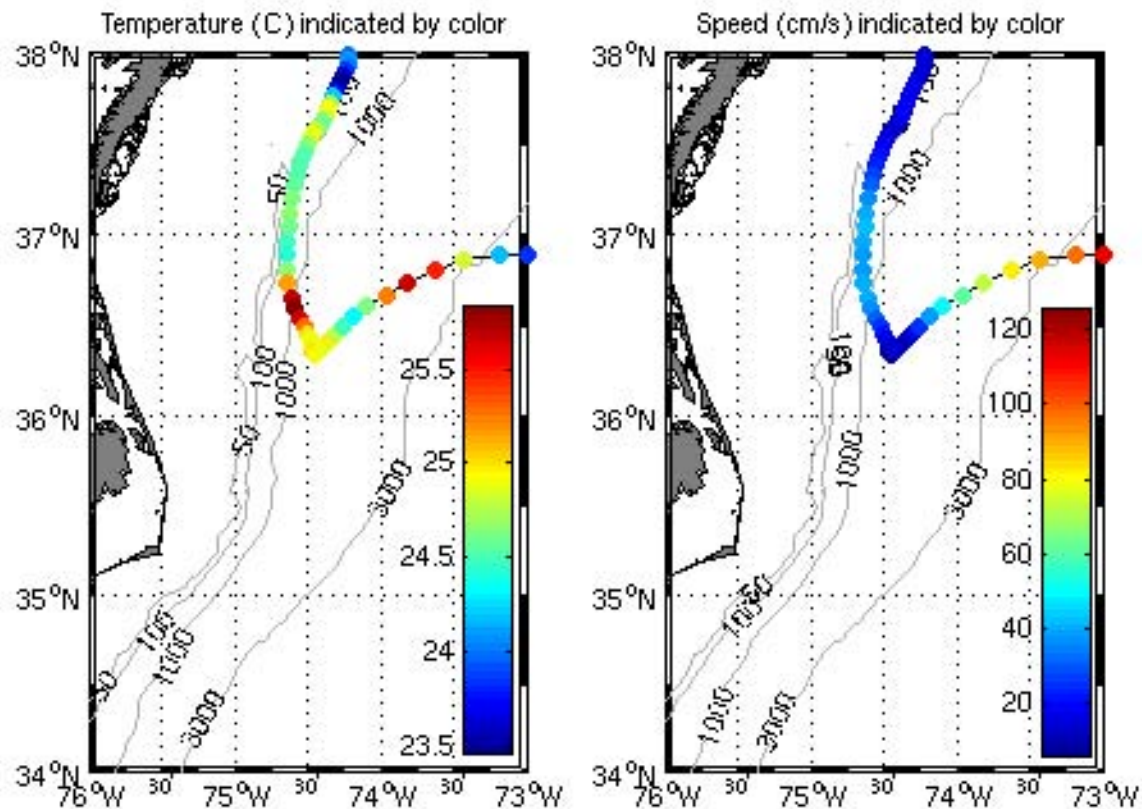


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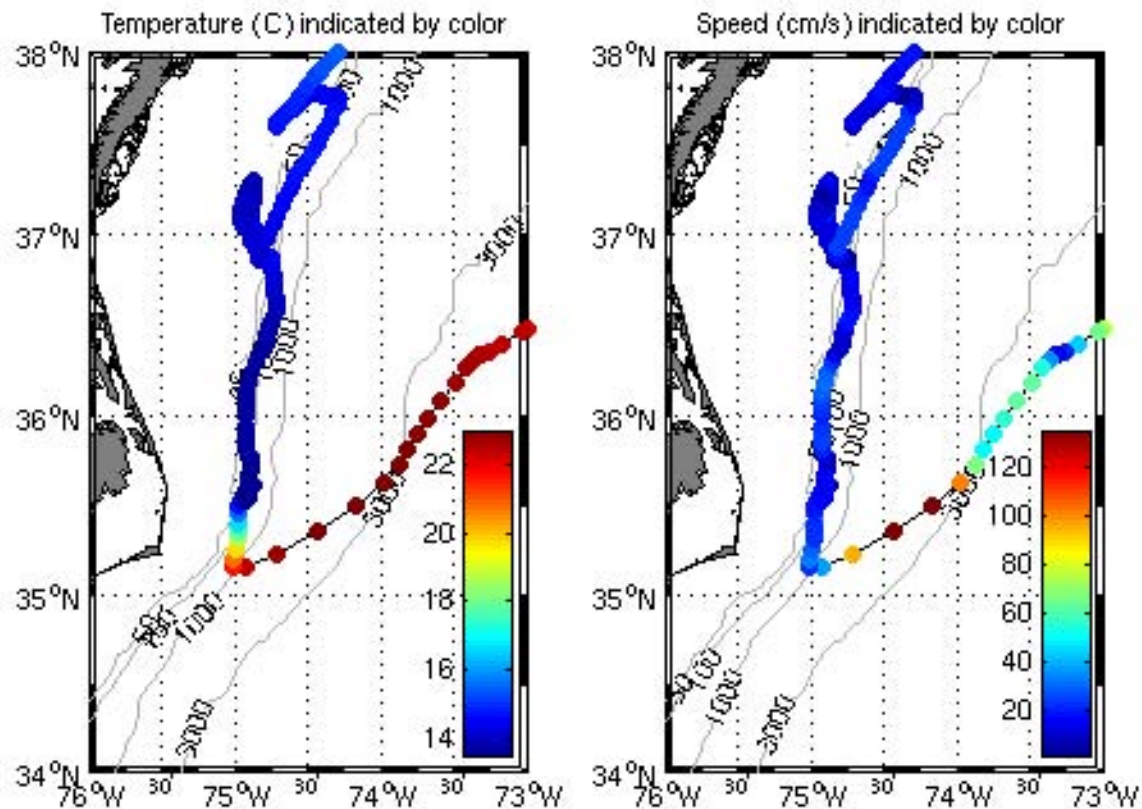


Figure 4

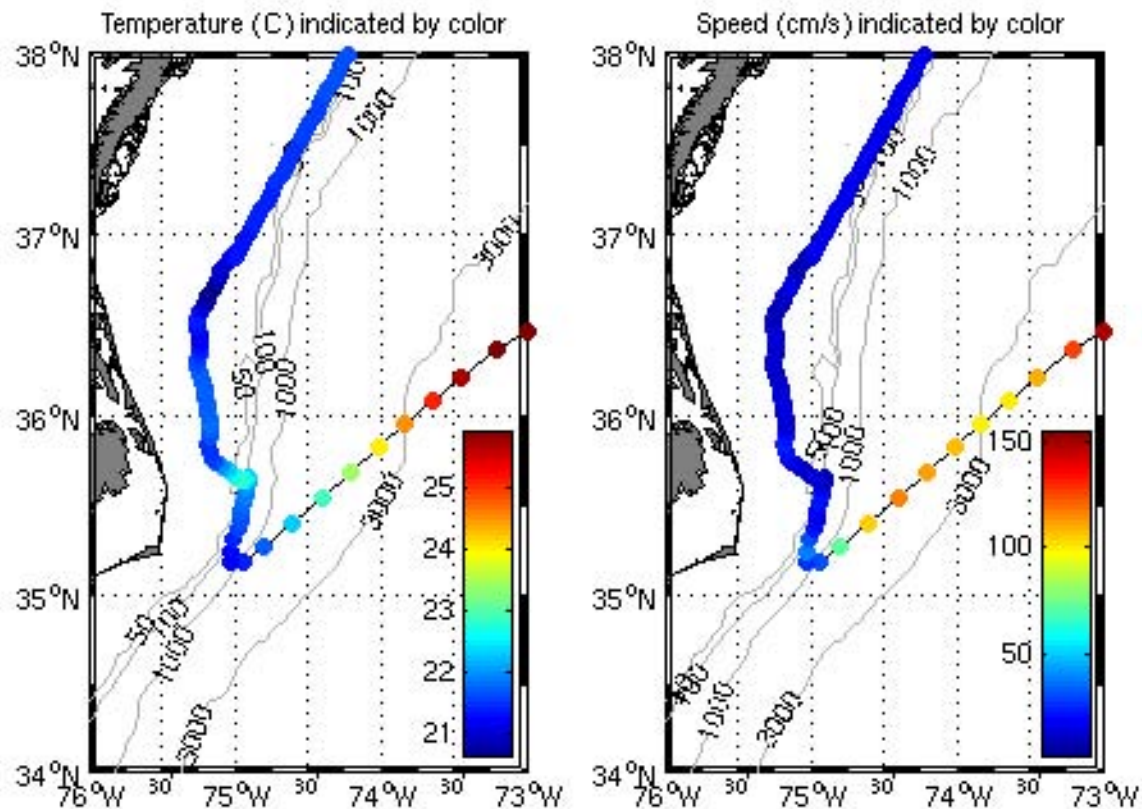


Figure 5

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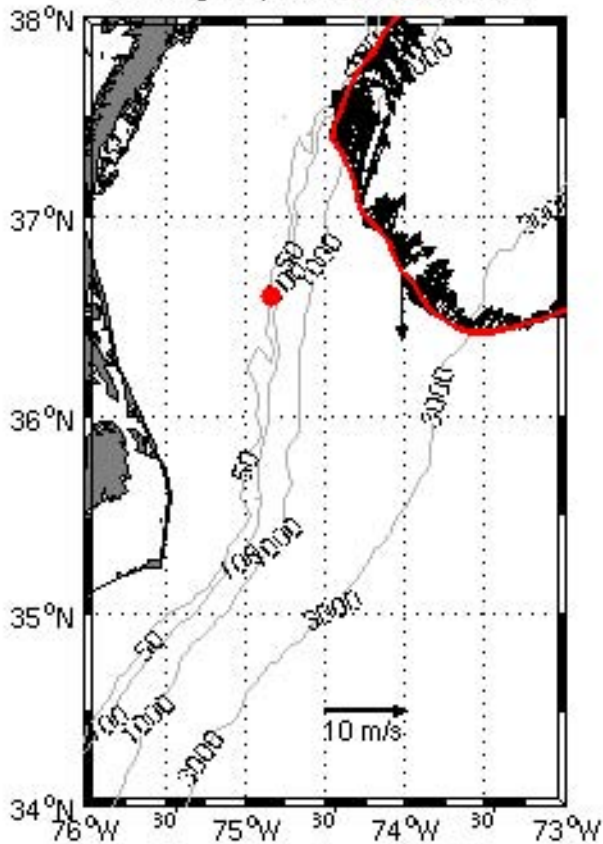


Figure 6a

NOAA-15 AVHRR 5/28/1999

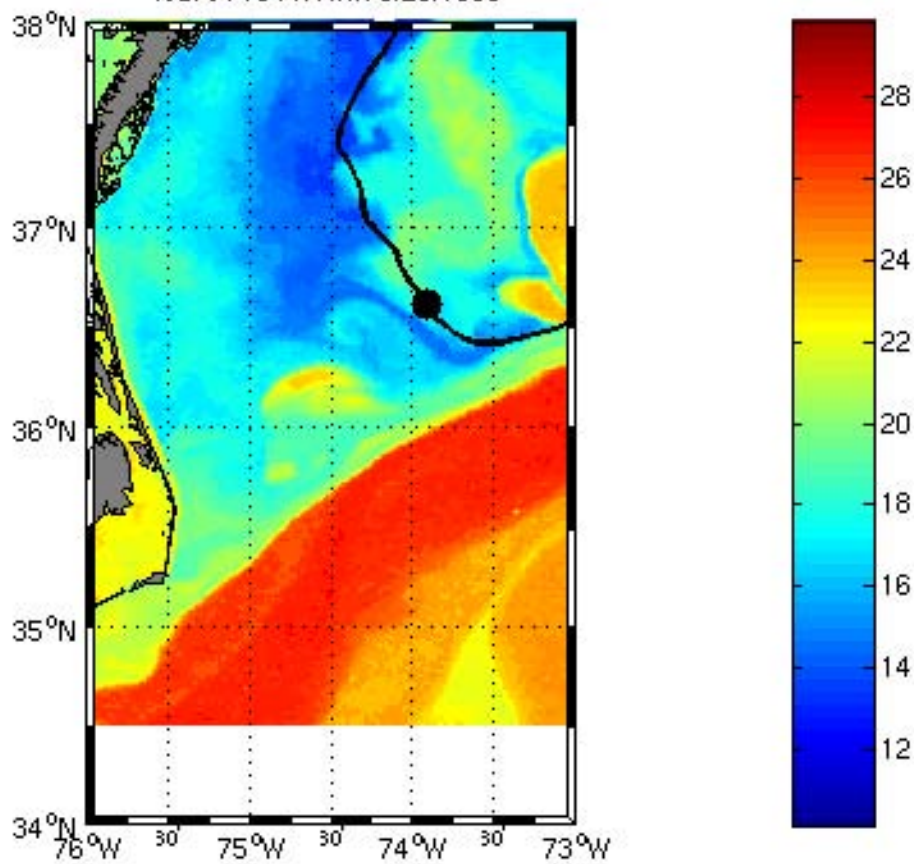


Figure 6b



Drifter g73lp: 8/20/1996-9/3/1996

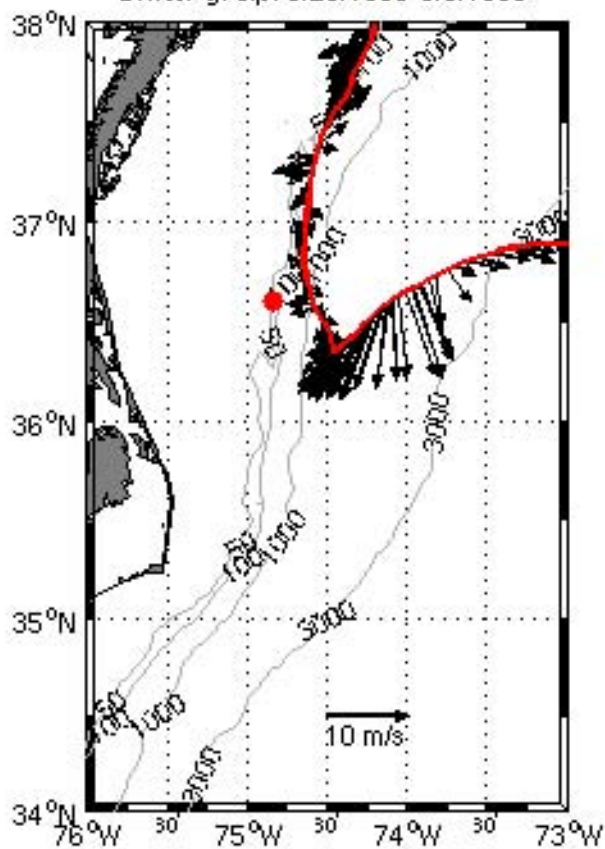


Figure 7a



NOAA-14 AVHRR 8/24/1996

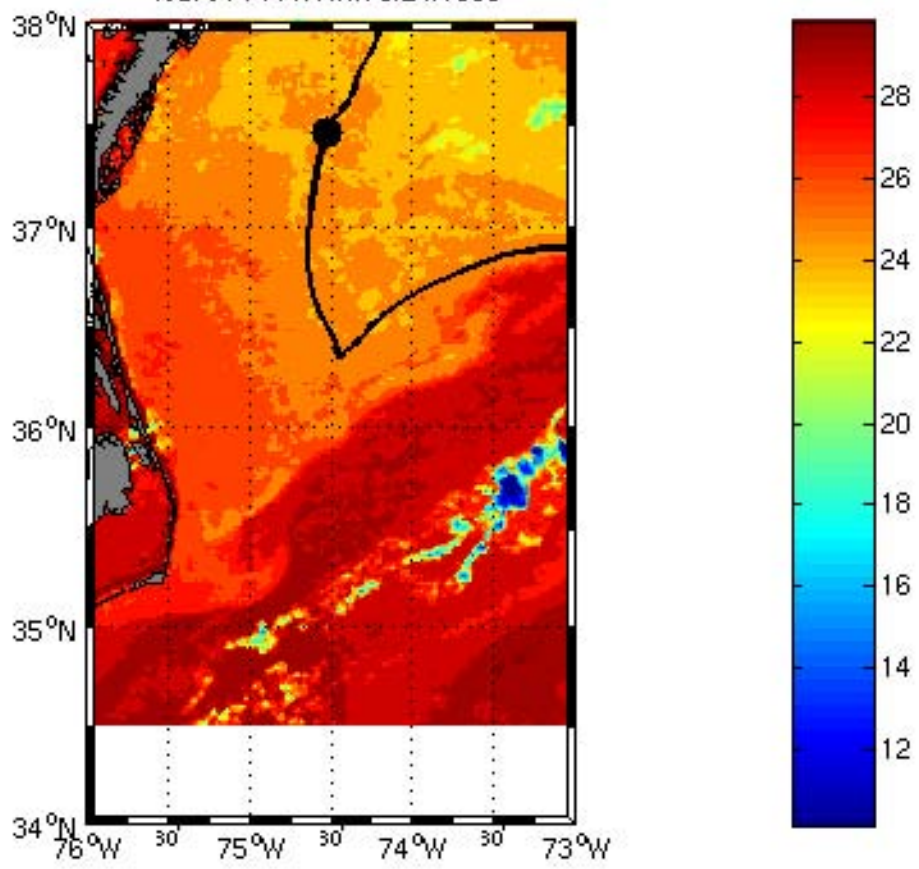


Figure 7b

Drifter g1611p: 11/7/1998-1/1/1999

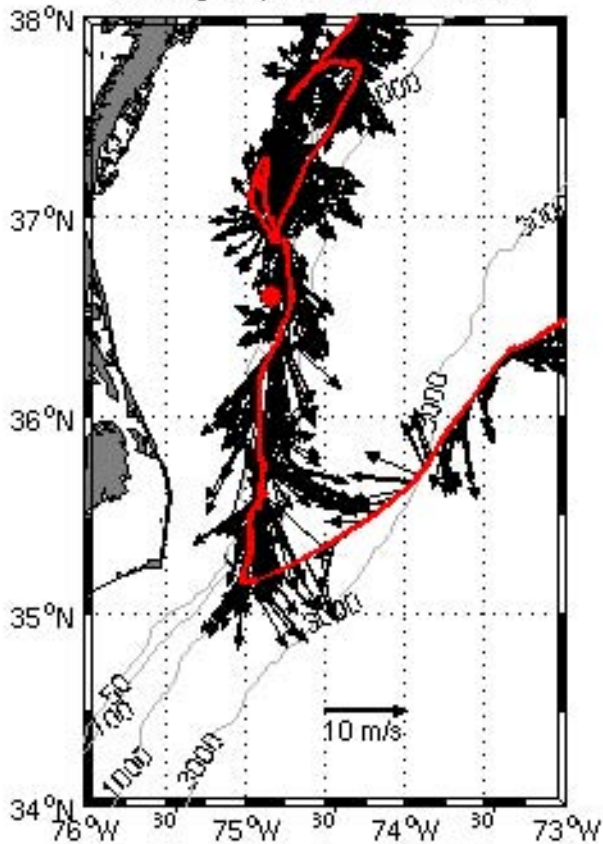


Figure 8a

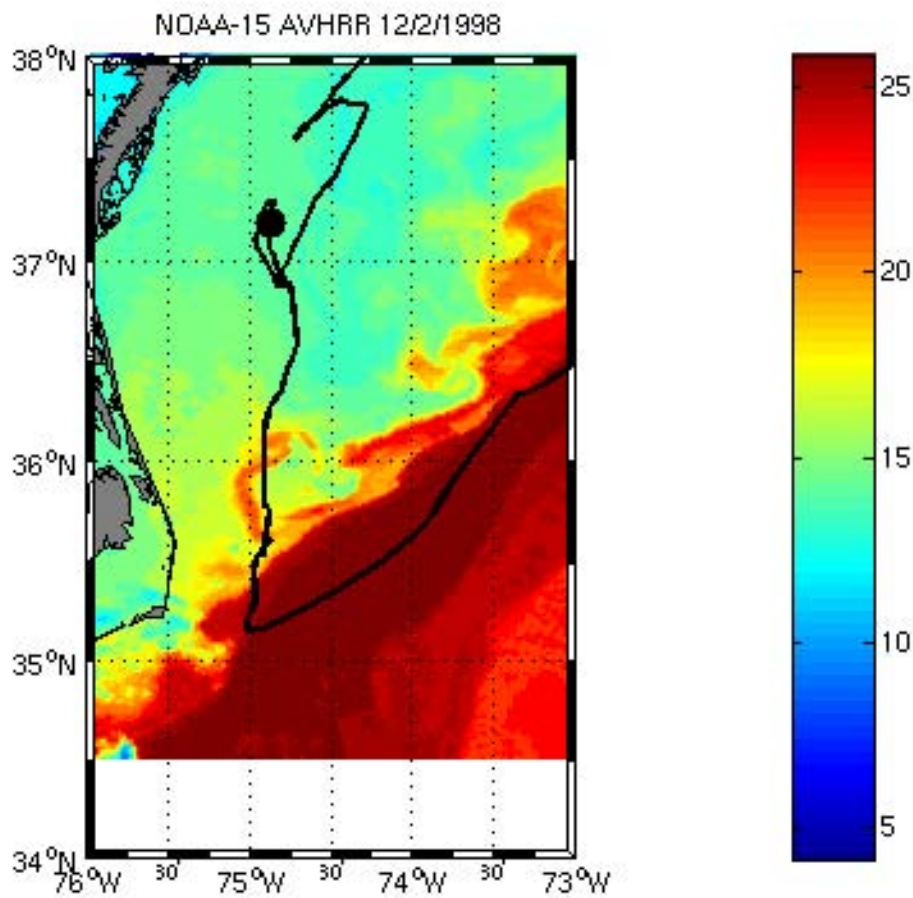


Figure 8b

Drifter g84lp: 9/21/1997-10/22/1997

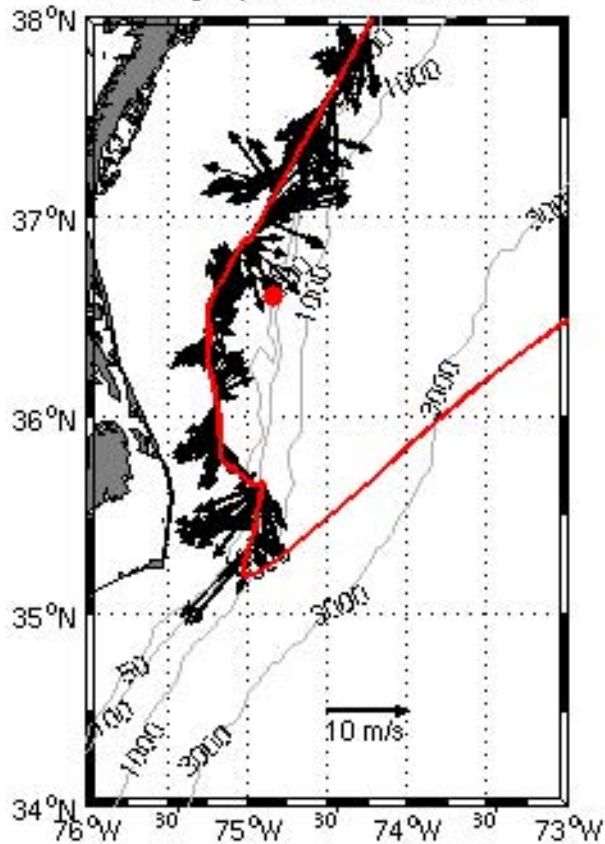


Figure 9a

NOAA-12 AVHRR 10/7/1997

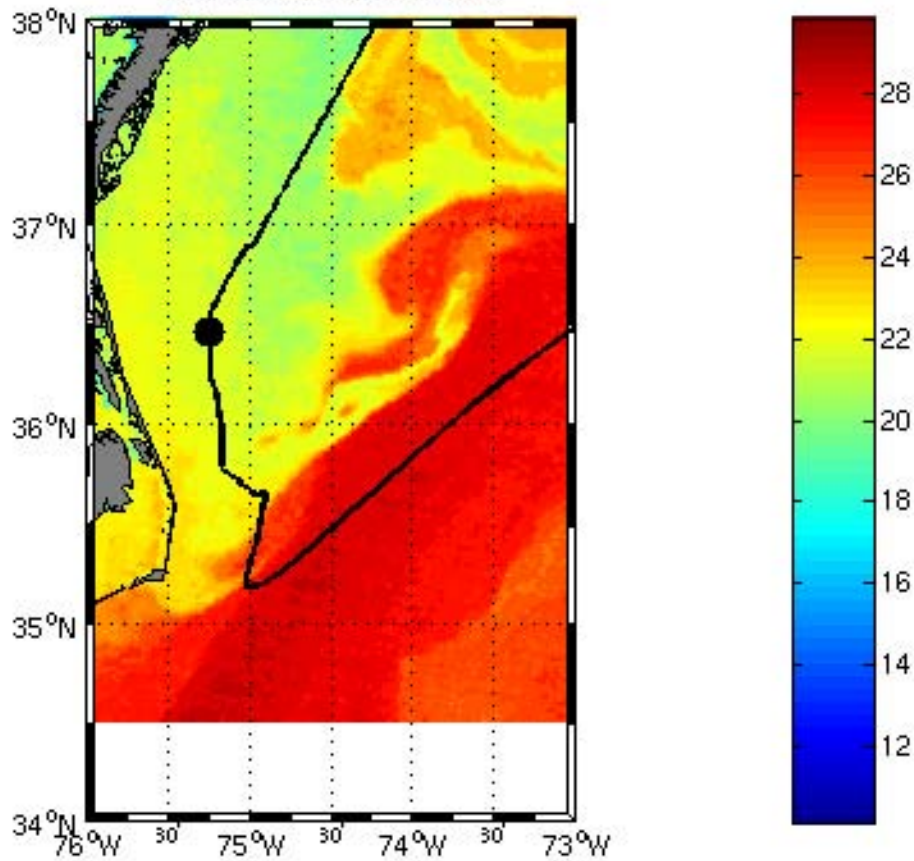


Figure 9b

Latitude=38 Degrees N

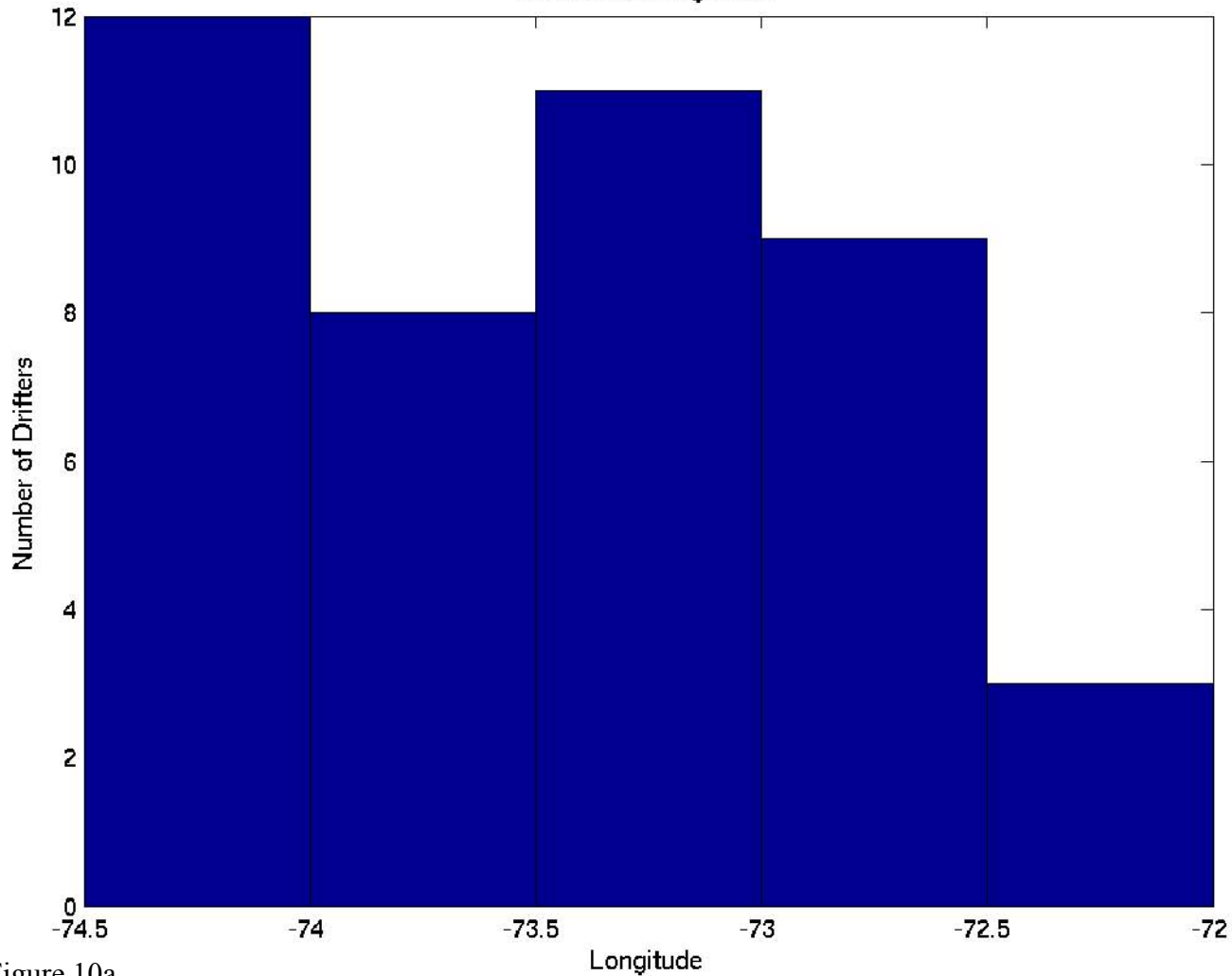


Figure 10a

Latitude=36 Degrees N

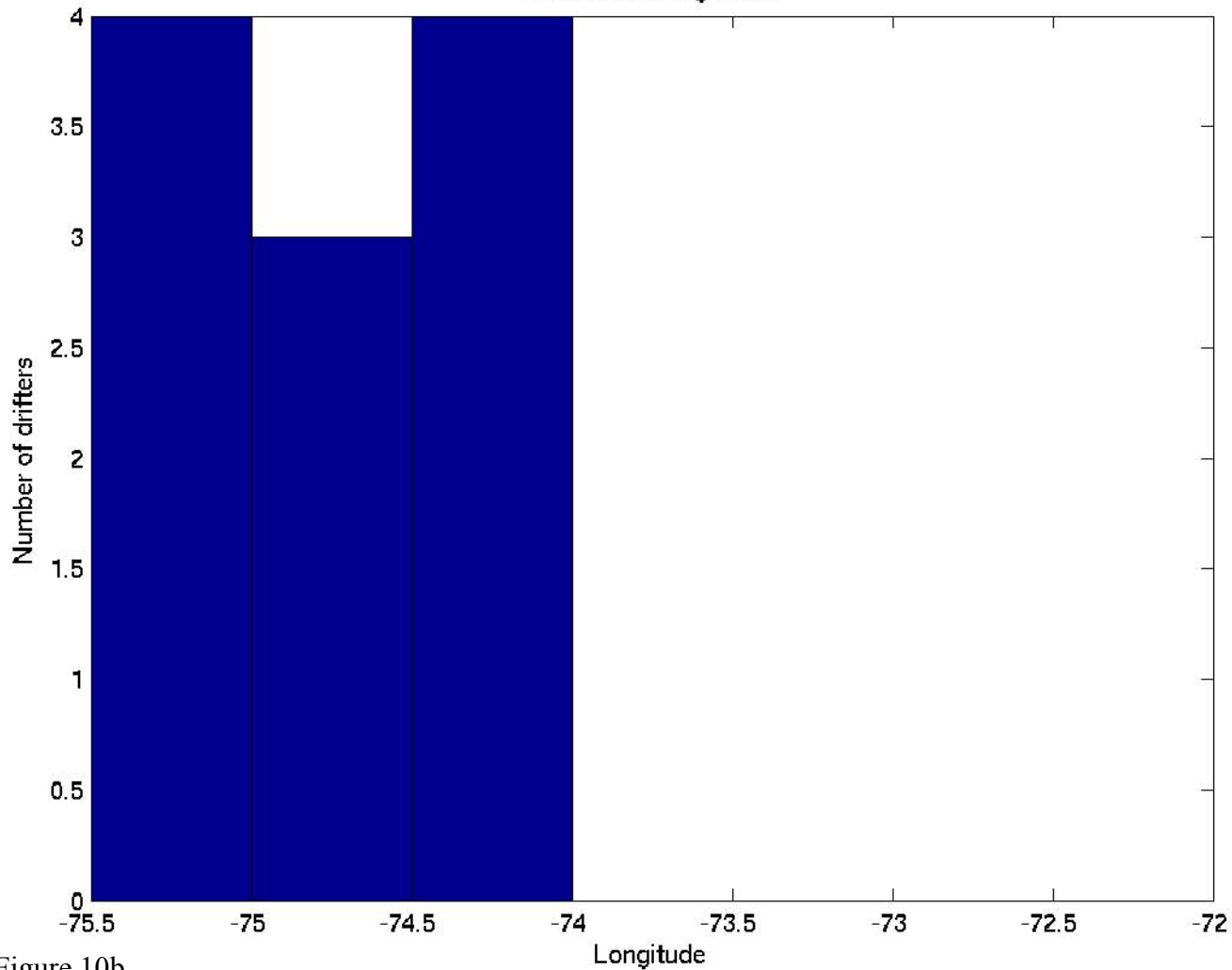


Figure 10b

Drifter g75lp: 11/23/1996-12/23/1996

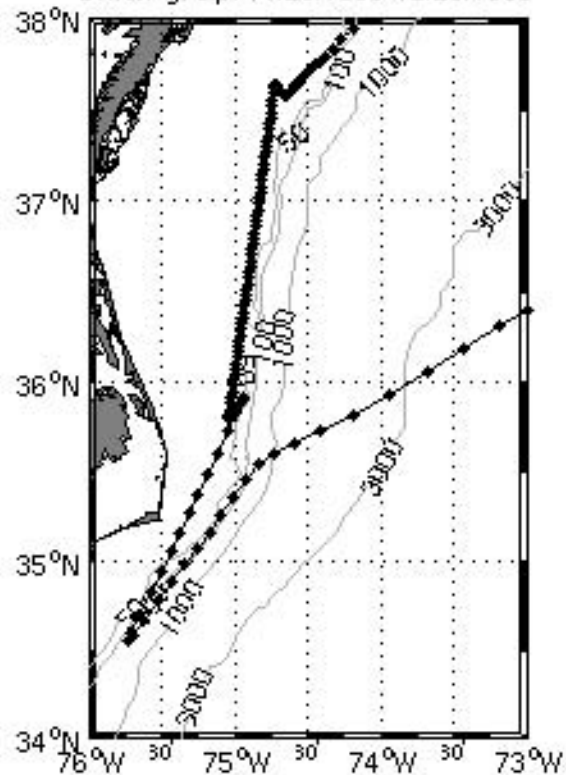


Figure 11a



Drifter g75lp: 11/23/1996-12/23/1996

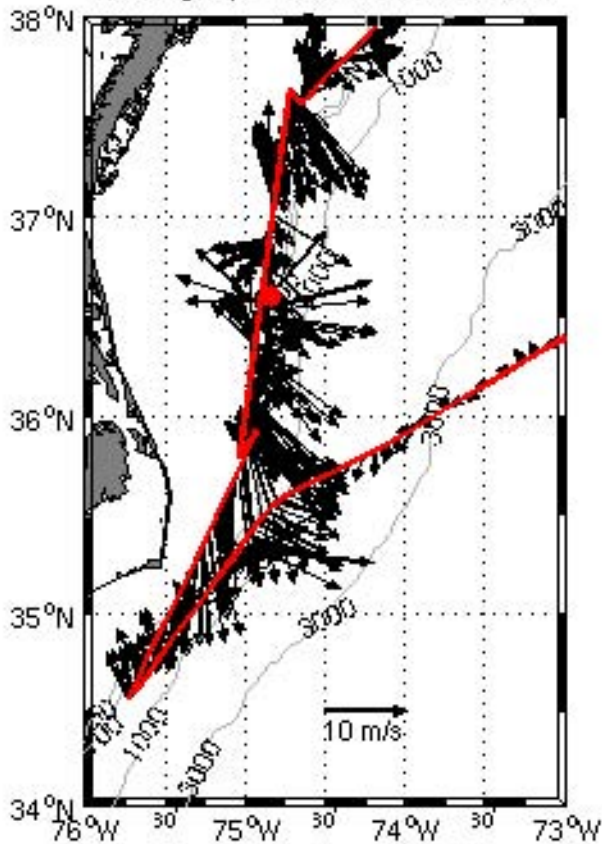


Figure 11b

NOAA-12 AVHRR 12/4/1996

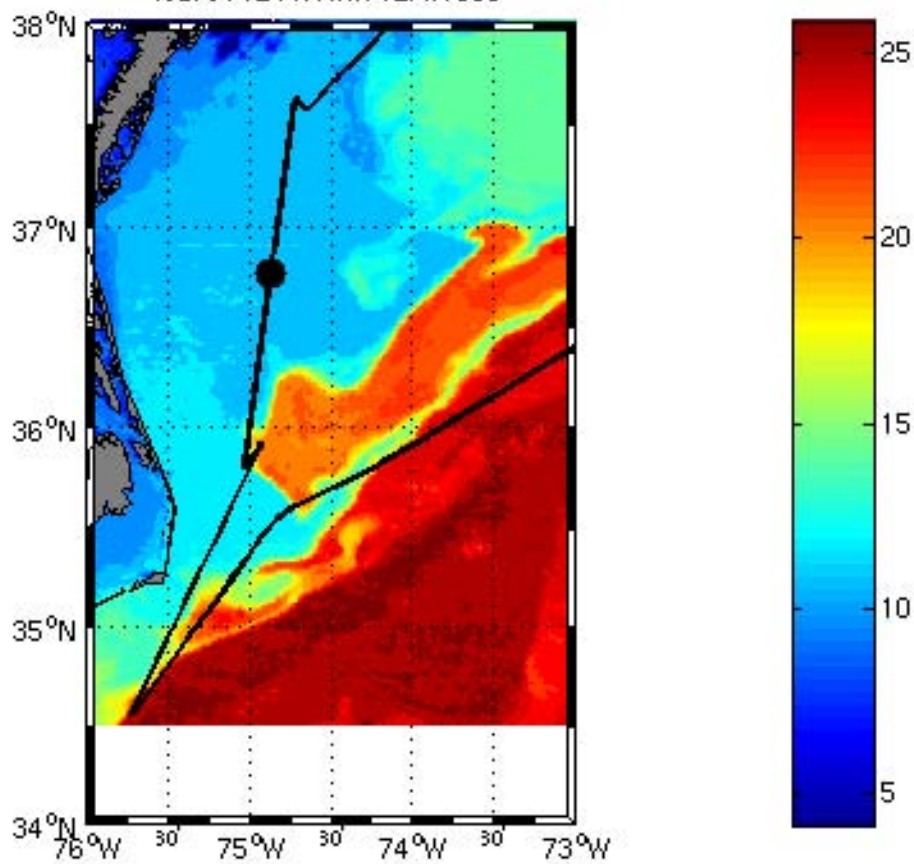


Figure 11c

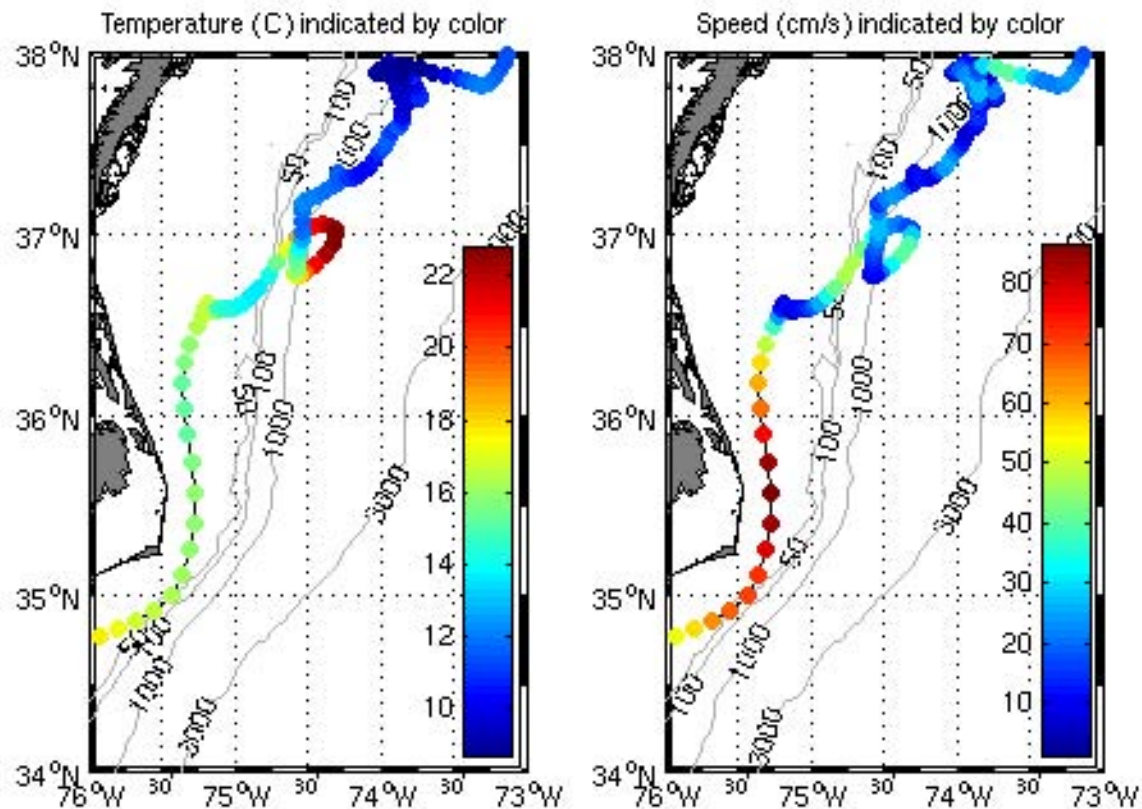


Figure 12a

Drifter g102lp: 4/27/1997-6/8/1997

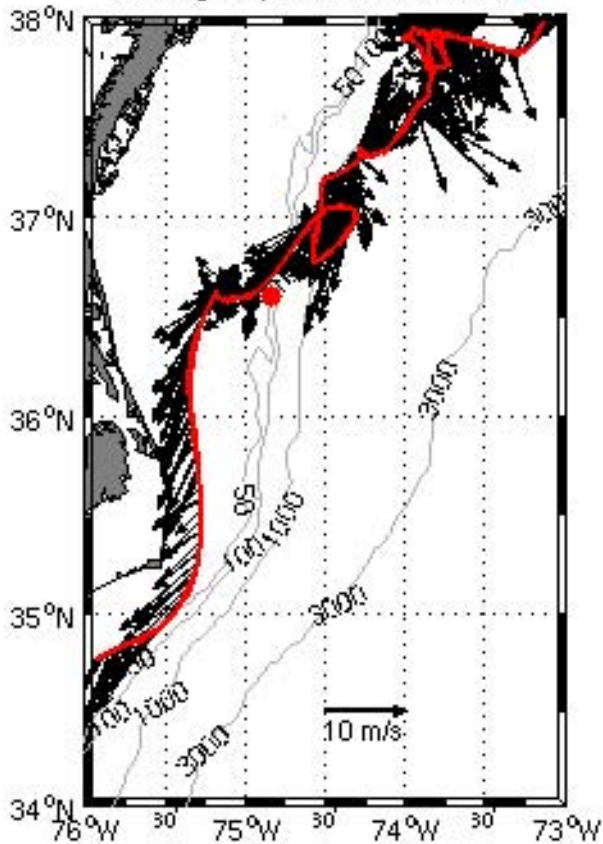


Figure 12b

NOAA-12 AVHRR 5/22/1997

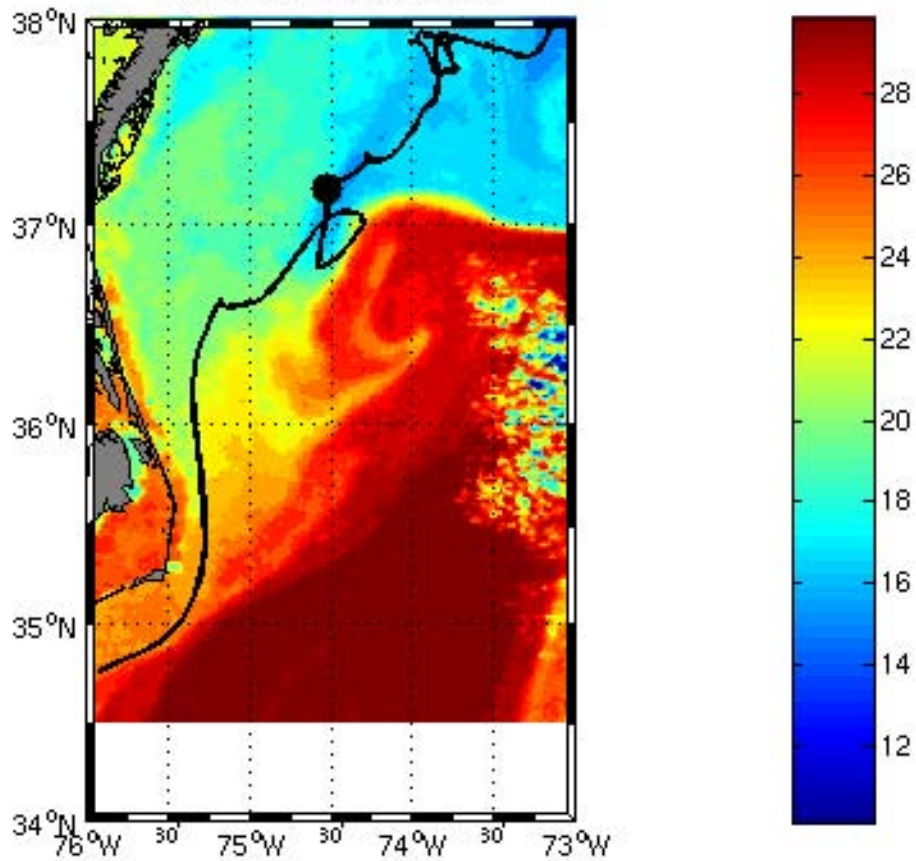


Figure 12c

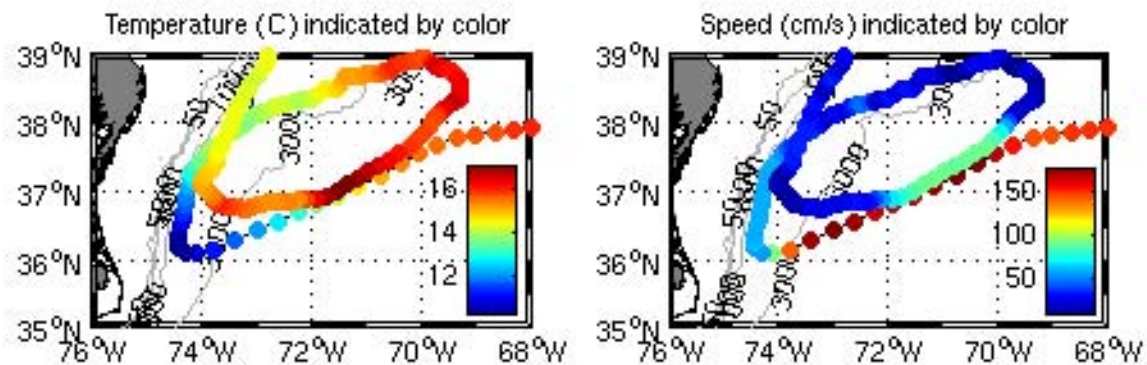


Figure 13

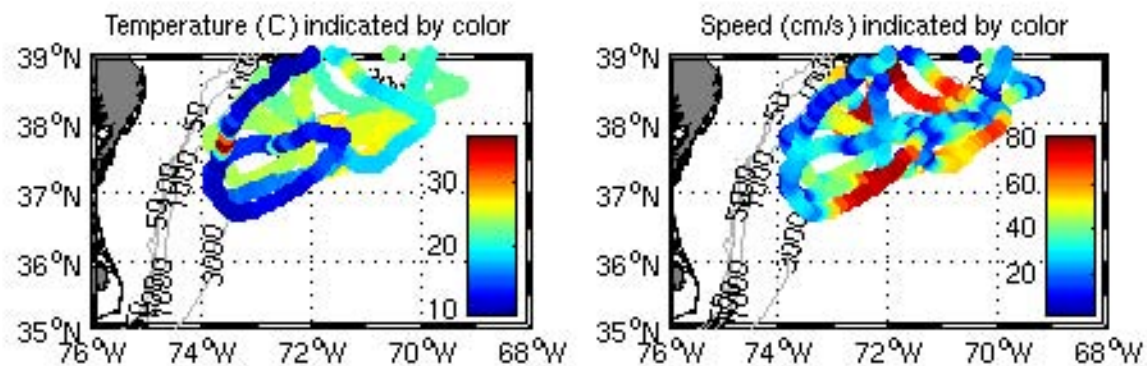


Figure 14

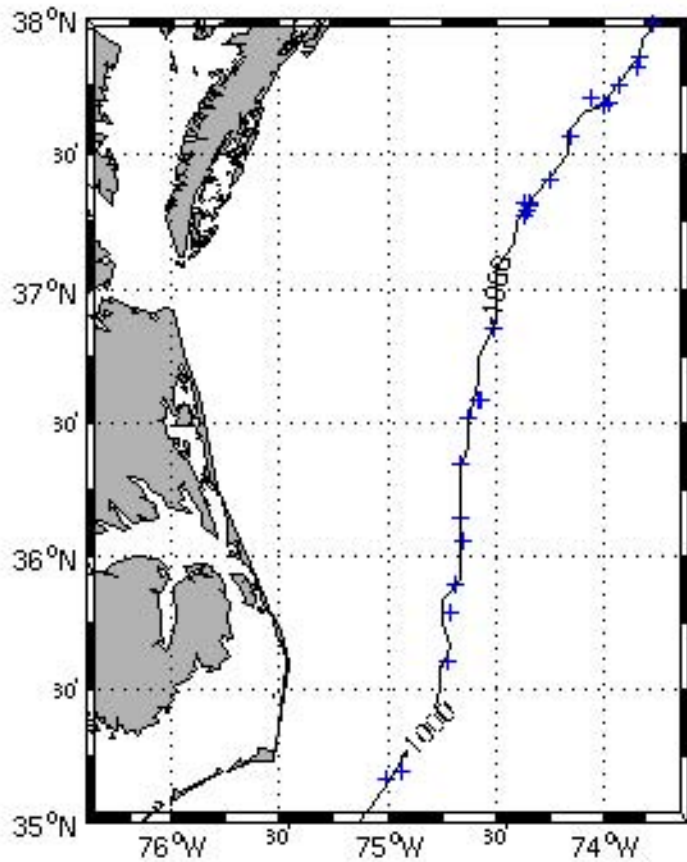


Figure 15a



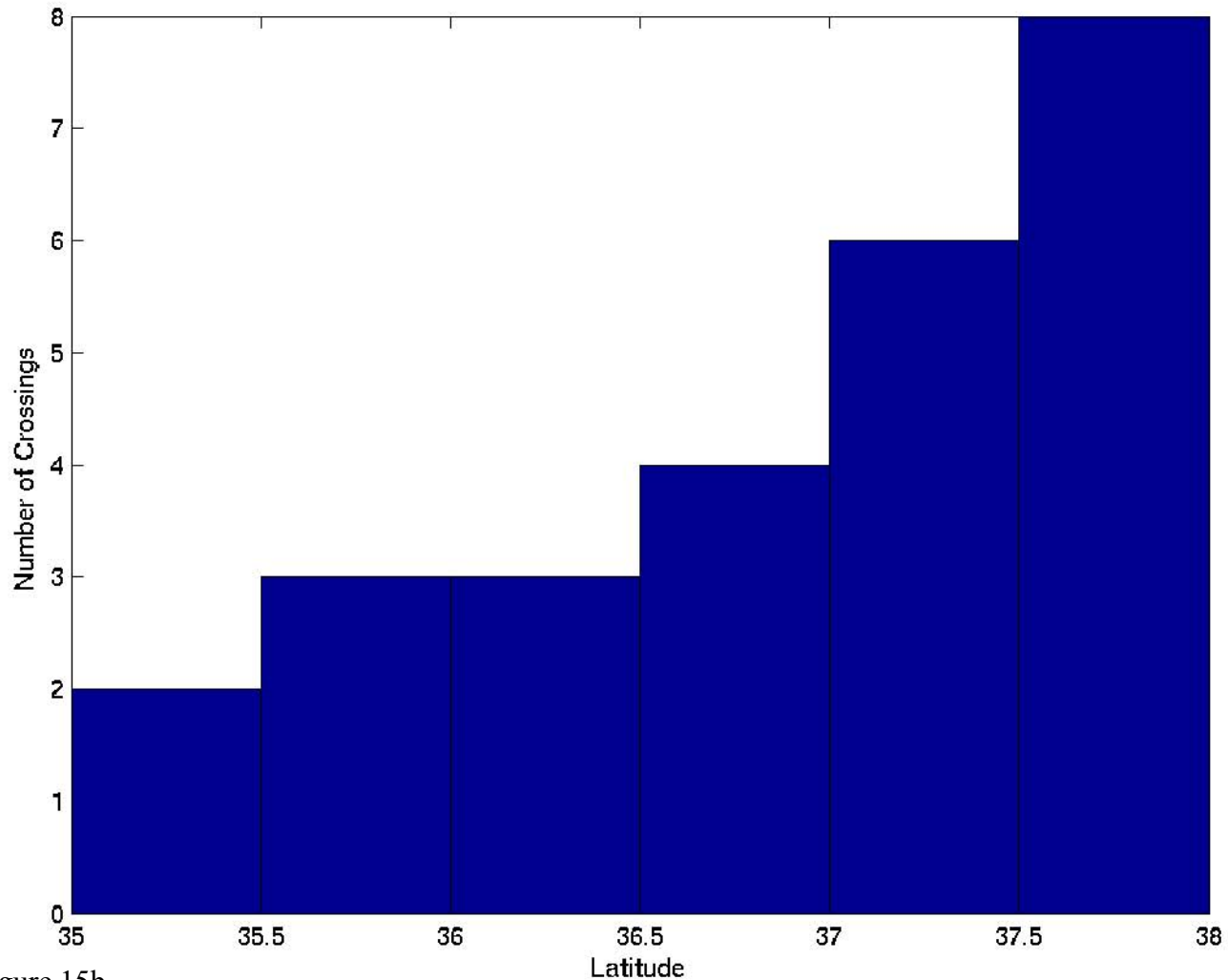


Figure 15b