Quantifying Transport Associated with Internal Waves in Massachusetts Bay

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Abstract

Previous studies have shown that large-amplitude internal waves are a significant agent in transporting particles, such as nutrients, larvae and effluent onshore. Data was analyzed from Mass Bay Internal Waves Experiment from 1998 in order to get an estimate of the currents and the transport associated with internal waves. Surface drifters were deployed in Massachusetts Bay, equipped with GPS devices to quantify the transport at a fixed depth. It was observed that the depth of the drogue below the surface was inversely proportional to the speed at which the drifter moved onshore. This study can be used to make a more comprehensive analysis of where and when the oil from a large-scale offshore spill may reach the shoreline.
Introduction

LIWs in Mass Bay

Large-amplitude internal waves (LIWs) are phenomena that are ubiquitous in bodies of water around the world, including deep oceans, bays and even lakes (Osborne and Burch, 1980; Halpern, 1971). They are believed to be important agents of mixing and transport of sediments, small biological organisms and pollutants. Previously, studies have provided the scientific community with qualitative information about the ability of LIWs to transport different objects. However, there remains a need to quantify the currents, timing and transport associated with internal waves in order to determine their precise role in the oceanic water column.

Large amplitude internal waves are formed when a stratified water column flows over uneven bathymetry in a periodic manner. Oceanic water can be stratified in density due to variations in temperature or salinity. Once the pycnocline or thermocline flows over a depression or a bank, a drop in the pycnocline is observed as well (Figure 1, Pictures 1-4). This internal disturbance would like to propagate, but the tidal current keeps it trapped. Once the tidal currents weaken, the waves propagate in the direction of the tidal current (Figure 1, Pictures 5-8). The large-scale depression evolves as the internal wave propagates, forming high frequency waves behind a steep bore-front. Not only has this phenomenon been observed in locations all around the world, it has also been modeled numerically (Lamb, 1994; Scotti, 2007).

Internal waves can significantly affect the near-shore ecosystem by transporting and mixing different sediments, pollutants and organisms. An analysis of the transport of
sediment in Massachusetts Bay due to internal waves has already been completed using
the data from MBIWE98 (See: Butman, 2006). The authors were able to quantify the
sediment that was being resuspended by analyzing the bottom currents and by using a
transmissometer to measure beam attenuation. Off the coast of La Jolla, California,
Shanks (1983) proved that crab larvae could be transported shoreward by unbroken
internal waves. Shanks (1987) also showed that LIWs should be considered when
calculating the dispersion of an offshore oil spill off the coast of North Carolina. Leichter
et al. (1998) showed that LIWs provide nutrients to benthic animals around the coral
reefs off the coast of the Florida Keys. Like Shanks and Leichter, we will be analyzing
the surface currents associated with internal waves in order to quantify the transport due
to this phenomenon.

Large-amplitude internal waves have been observed in Massachusetts Bay (Mass
Bay) for over 30 years. Halpern (1971), Haury et al. (1979), Chereskin (1983), Trask and
Briscoe (1983) have all described interactions of nonlinear internal waves in Mass Bay.
During the summer, a pycnocline develops about 20 meters below the surface, where the
top layer is warmer due to solar radiation and less dense due to freshwater streams. This
is a popular site to study internal waves because it is a comparatively controlled
environment where internal waves dominate over other physical phenomena. LIWs are
generated as the tidal current flows over Stellwagen Bank when the water column is
stratified. This bank provides a ridge that substantially disturbs the pycnocline (Figure
2). These waves propagate to the southwest where they shoal and break. They occur in
packets of 5-10 waves that propagate shoreward at around 0.8 m/s soon after the
maximum high tide.
Motivations for DyeWaves08

Despite research performed by Shanks, Leichter and others, a quantitative study on the transport associated with internal wave packets has not been performed. This paper includes preliminary data gathered from a cruise on Massachusetts Bay in July-August 2008 (DyeWaves08). There were many components to this cruise, including fixed moorings, dye and surface drifter deployments. The fixed moorings and the CTD casts were used to get a picture of the density field. The ADCPs on the fixed moorings were important to get a profile of the currents throughout the entire water column. From this data we can get an estimate of transport using integration methods such as the Runge-Kutta method (See analysis of MBIWE98 data). The drifters can also be used to estimate transport, but like the integration methods, are constrained to a single depth. Dye, on the other hand, is free to move up and down the water column, much like organisms or pollutants. By measuring the concentration of dye in the water as an internal wave passes by, we can get a much more accurate picture of how organisms can be transported by these internal waves.

MBIWE98

Introduction

In preparation for analysis on the data collected from DyeWaves08, we consulted the data taken from Site C of the Massachusetts Bay Internal Wave Experiment in 1998 (MBIWE98). This data has been analyzed in other papers, including Butman et al. (2006), which focuses on the transport of sediment due to these waves and Grosenbaugh et al. (2002), which reports on the performance of the MBIWE98 horizontal array. Site C
was located at 42 14.7’ N, 70 33.2’ W, at 50 m water depth. At this mooring site there was a temperature, conductivity and pressure (TCP) instrument placed on the seafloor. Also, there was an Acoustic Doppler Current Profiling (ADCP) instrument attached to a tripod on the seafloor, measuring the current. From the data collected by the ADCP, I was able to analyze the kinematics of large amplitude (nonlinear) internal waves, as well as the timing and the transport due to these waves.

**Kinematics**

The motion of internal waves is difficult to measure simply by watching them propagate in the ocean. Their presence can be seen at the surface by lines of slick water with areas of rough water in between. However, in order to quantify the currents in an internal wave, ADCPs can be used in order to determine the vertical structure of the currents and how the wave is moving through the ocean. By plotting the currents in the direction of the wave propagation and the vertical currents associated with a wave packet we can begin to visualize the kinematics of an internal wave (Figure 3). As a wave packet moves by, the currents closer to the surface move in the direction of wave propagation, while the currents near the seafloor move in the opposite direction. When just these bins (44 mab and 10 mab) are plotted, it becomes clear that the horizontal currents at the top and the bottom of the water column are 180° out of phase (Figure 4a). The vertical currents, however, lead the horizontal currents by 90°, which is true of an idealized wave function (Figure 4b). At a peak of a wave, the currents are all in the horizontal direction, while halfway between a peak and a trough the vertical currents will be at a maximum. The currents associated with an idealized internal wave are shown in Figure 5.
Timing

From various analyses of the data collected from MBIWE98, we now have a good understanding of where these waves are generated, how they are propagating and what they look like (i.e. Butman 2006, Scotti 2007). However, we only have a rough idea of when they will be generated and when they will arrive at different locations. Using the data from Site C, we plotted the arrival time of the internal wave relative to high tide (Figure 6) and the arrival time of the internal wave relative to the previous internal wave over the duration of the experiment (Figure 7). As expected, on average the internal wave arrived approximately 12.4 hours (a period for a semidiurnal tide) after the previous internal wave. However, there was a significant range of arrival times, with a standard deviation of 1.13 hours. From this data, we were able to show a weak correlation between tidal amplitude and arrival time (Figure 8). The internal waves could propagate past Site C anywhere from 1 to 6 hours after high tide at Site C. The variance of the data points relative to the fitted line was 0.85±0.73 hours. However, there was a much stronger correlation between the arrival time of an internal wave packet relative to the previous internal wave packet and the amplitude of the tides relative to the tidal amplitude of the previous tidal cycle (Figure 9). Here, the variance of the data points relative to the fitted line was 1.06±0.67 hours. Scotti et al. (2007) also found such a correlation when he analyzed the data at Site B. They explained this correlation by reasoning that an increase in tidal amplitude causes an increase in the forcing strength that moves the pycnocline depression further downstream, which results in a delayed wave propagation.

This analysis was extremely useful in the DyeWaves08 cruise. By having a general idea of when an internal wave was going to propagate over Stellwagen Bank, we
could prepare the dye and the drifters and get the boat in the right position for the deployments. As the data suggested, at sea we found there to be a stronger correlation between the relative amplitude of the high tide and the relative timing of the internal wave, rather than the absolute tidal amplitude and the absolute timing of the wave after high tide. However, even with these analytical tools we could only predict the appearance of the internal wave packet within about a 1-2 hour range.

*Transport*

By cumulatively summing the average surface current over the duration of the experiment, we could get a baseline estimate of how far an object might travel. Figure 10 shows that over a period of a month, an object could be transported approximately 50 km. This is a significant distance, since Stellwagen Bank is around 40-50 km away from the Massachusetts shoreline. We were also able to estimate the transport per internal wave packet, by summing the currents from 1 hour before the arrival of the first wave to 1 hour before the arrival of the next wave packet (Figure 11). The cause of the peaks in transport is uncertain. We could get a more accurate idea of the transport associated with these internal waves by using the Runge-Kutta integration method. This analysis allows for us to take into account the fact that wave packet is traveling onshore as well. Before we could just use the current data, but by considering the phase speed of the internal wave packet, which we estimated to be 0.75 m/s, we can see how the estimated transport is larger than we first imagined (Figure 12). By simulating the currents at 5m depth and 8-12 m depth, we can estimate how far the drifters could go if they were entrained in a wave packet.
GPS Packages

Description

Precise GPS locations were necessary in order to quantify how far the drifters or the moorings moved as an internal wave packet propagated over them. GPS chips were purchased from Spark Fun Electronics (GPS Logger v2.4) in order to attach to the 4 fixed moorings and to 2 holy sock drifters that were used in the DyeWaves08 experiment. Also, we could match the timing For the GPS chips that were attached to the guard buoys of the moorings, 4 Li-ion batteries were used to ensure an adequate battery supply for 70 days. They were set to sample every 90 seconds, with a hold-off time of 35 seconds. The chips were placed between discs of hard plastic, ½ in thick, 2 in radius and 1-½ spacers were used to separate the chip from the bottom disc. Larger spacers were used to separate the discs of plastic. These contraptions were placed in 4 ½ in OD PVC piping along with chunks of polyurethane foam in order to prevent any movement from the sloshing of the guard buoy on the surface of the ocean. The bottom of the PVC pipe was attached to the tube with PVC glue, while the top was connected with Slic-Tite, in order to ensure proper waterproofing. For the GPS chips that were attached to the flagpole of the holy sock drifters, 4 alkaline C batteries were sufficient in order to provide enough power for multiple hours. Thus, this reduced the size of the PVC piping necessary to keep the GPS chip dry. Instead, the plastic discs were cut with a diameter of 2 in and were placed in 2-½ in OD PVC piping.

Testing
To determine the accuracy of the GPS chips we calculated the standard deviation from the mean location for a number of different GPS settings. Hold-off time (HOT) roughly represents the amount of time spent searching for GPS satellites, while time between logs (TBL) represents the amount time the device spends ‘sleeping’ in between samples. We ran these tests in the OSU football stadium parking lot on a clear and warm day. We chose these conditions because the parking lot is fairly open, without much interference from buildings or trees, in order to simulate the environment of the open ocean. Figure 13 (solid lines) shows that, as the hold-off time drops from 10 seconds to 1 second there is large increase in accuracy for all TBL times. However, as hold-off time increases the amount of charge needed increases as well because while the device is searching for satellites, it uses about 115 mA. The thick black line represents the amount of ampere-hours from four Li-ion batteries, the maximum amount of battery power that could be used. For the GPS devices on the drifters, we could have a faster sampling rate, since we could replace the batteries every 2 days or so (Figure 14). Thus, it was determined that the HOT should be 10 seconds and the time between logs should be 20 seconds.

**Filters**

In order to maximize the accuracy of the GPS units as well as minimize the amount of battery power needed, it was necessary to find a balance between the HOT and the TBL. In doing so, we had to increase the standard deviation of the GPS chip when it was not moving. This could be reduced, however by filtering how the data points with bad satellite fixes. The NMEA sentences that were recorded by the GPS chip included information on the number of satellite fixes and the horizontal dilution of these fixes. It is
imperative that the GPS satellites are spaced out throughout the entire sky in order to the unit to be able to triangulate its location. Thus, if the number of satellites it receives data from is small, or if the satellites are in relatively the same location, then the GPS position can be fairly inaccurate. For the GPS units on the moorings, with a longer HOT, we determined that an accurate data point should have at least 5 satellite fixes and a horizontal dilution of less than 2. While for the GPS units on the drifters, at least 3 satellite fixes and a horizontal dilution of less than 5 would be sufficient.

DyeWaves08

Overview

From July 26 – Aug 3, we were on the R/V Cape Hatteras in Massachusetts Bay, traveling on a transect line from Scituate out to Stellwagen Bank (Figure 15). During the first day of the cruise, we deployed 4 moorings and tripods at precise locations near or on the transect line (Figure 15). The moorings consisted of a guard buoy that floated on top of the water and CTD instruments that were spaced out every 5-10 m. Also there was an ADCP 5 m below the surface in order to get a profile of the surface currents. The tripods were equipped with an ADCP to measure currents throughout the entire water column, an ADV to measure turbulence and stress and an acoustic release in order to recover the tripod. They were deployed as close to the moorings as safely possible. We chose these spots to deploy the buoys and tripods because it would give us a clear picture of an internal wave packet as it is generated over Stellwagen Bank and as it travels onshore. As the total amplitude of the wave approaches the depth of the water, the wave begins to shoal and break. Thus, three of the buoys were placed in close proximity to each other in
order to get a higher resolution of what happens to the currents as the wave is shoaling. After the moorings and the tripods were deployed, we used a ScanFish, owned by the University of Delaware, to get a high resolution picture of the density field over the transect line. After the Scan Fish was used, we replaced it with an instrument package that could measure temperature, conductivity, density, chlorophyll and fluorescence. This package was raised and lowered by a wench when the boat passed through an internal wave packet in order to give a real-time picture of how the waves were affecting the water column.

The majority of the cruise was spent chasing wave packets and deploying dye. When a wave packet was spotted, either on the radar or on the boat’s ADCP, a dye deployment was prepared on the boat. Ideally, we laid out a line of dye perpendicular to the direction of wave propagation ahead of the oncoming leading edge of the wave packet. However, due to uncontrollable factors, such as the boat’s speed and location, this goal was not achieved perfectly. After deploying the dye, we set a course to zigzag through the dye, in order to obtain fluorescence data. This would tell us how the currents in the internal wave packet were dispersing the dye. Before, during or after deploying the dye, 2-4 surface drifters were deployed. There were 2 Davis drifters and 2 holy sock drifters available to use. Davis drifters could only be drogued at a depth of 0-1 m, while the holy sock drifters could drogued at various depths from 1m to 15 m below the surface. The holy sock drifters were equipped with GPS devices that sampled approximately every 30 seconds. From this data, we were able to obtain a clear picture of the movement of the drifters over time.

Results
Over the course of the research cruise, 5 dye deployments were performed and both of the holy socks were used in the last 4 deployments. The preliminary results from these deployments are listed in Figure 16. This table shows the wave packet’s name and date, what types of drifters were deployed, what depth they were deployed at, the total transport and the total transport velocity in the North-South direction and the East-West direction, and the magnitude of the transport velocity. High-resolution GPS chips could not be attached to the Davis drifters, so we do not have GPS data for those drifters in this paper. The holy sock drifters were meant to be drogued at a depth of 4-7 m below the surface of the ocean. However, either the added weight of the drogue was not sufficient or the cords attaching the drogue to float got tangled, so that the drogue did not deploy properly and was stuck near the surface. However, these unforeseen mishaps allowed us to estimate the transport at different depths.

The absolute GPS positions of all of the drifters are shown in Figure 17, while the relative movements of the drifters are shown in Figure 18. In this figure the data is manipulated so that the drifters start at the same spot at the same time. This can allow us to see how the drifters moved in time relative to each other and can also give us an idea of the distances that these drifters move. By just using the starting and ending points of the drifters, we can calculate the transport velocity of each drifter (Figure 19). It is apparent that the deeper the drogue is in the water, the slower the transport velocity. This makes sense, since the strongest currents associated with the internal waves are right near the surface.

By just focusing on the time when the drifters are moving southwest when they are entrained in the internal wave packets, it becomes easier to see how these waves
directly effect the movements of the drifters. Figure 20 shows the positions of the drifters while they are entrained in the wave packets. They are all moving in the western or the southwestern direction, which is the general direction that the waves are propagating in. If we plot their relative positions we can see that one drifter, in particular, was transported nearly 1.5 kilometers in a little more than an hour (Figure 21). We could actually see from the boat that this drifter was stuck in the leading edge of Puck. Thus, it is logical that this drifter would be transported the furthest in the southwestern direction. By plotting the North-South velocity component, the East-West velocity component and the total magnitude of the velocity all relative to the depth of the drogue, it becomes apparent that Western velocity component is inversely proportional to the depth of the drogue (Figure 22). However, we cannot say the same for the North-South velocity and also the magnitude of the velocity.

Discussion

Drifter Explanation

In order to explain the paths of the drifters that were not influenced by the internal waves propagating to the southwest, a number of techniques were used. First, wind data was taken from the National Buoy Data Center, operated by the National Oceanic and Atmospheric Administration. Either the wind could have pushed the flagpole of the holy sock drifter in the direction that the wind was blowing or sustained winds on the ocean could have led to Ekman transport, which would transport the drifters 90 to the right of the wind direction. By analyzing the data from Buoy 44013, located 20 nautical miles east of Boston, we could estimate the winds that the drifters were exposed to while in the
Figure 23 shows a compass of the composite wind data from July 28 to Aug 3—the period of time when we deployed the drifters. Although there were strong winds to the southeast and the west, these winds would have to be sustained in order to contribute to the movement of the drifters. Figure 24 shows that the strong winds were not sustained for more than a day, no matter what direction they were blowing. Thus, the westerly winds may have caused the drifters in Maximus to head west or the drifters in Kenji or Ishmael to head north, but it probably was not the most significant source of transport.

The finite-volume coastal ocean model (FVCOM), designed by Shengchen Chen, can model the near-surface currents in Mass Bay at one-hour increments. Although I was not able to obtain data for the time period when the drifters were in the ocean, I was able to get data for the same time period after high tide. Since we always deployed the drifters 1-5 hours after high tide, the tidal flow was always from heading away from Mass Bay. This is apparent in Figure 25, which shows a vector field of the near-surface currents 4 hours after high tide on August 14th, 2008. When the ebb tide empties out of Mass Bay, it flows in the northerly direction. Thus, this may explain why the drifters in Wave Kenji and in Wave Ishmael turned north.

*Hypothetical Transport*

Using the data from the drifters we can come up with a hypothetical transport of particles around Mass Bay. It would be difficult to estimate the transport of nutrients or larvae because they can move around in the water column. Once we can successfully track the dye, we will be able to make more definitive conclusions about the transport of such particles. However, we can make more accurate assessment of how a hypothetical oil spill might be transported by using the two holy sock drifters that were 1-2 m below
the surface. Since oil will always float on the ocean surface, this is an accurate prediction of how flotsam on the surface will be transported. One of the drifters that was on the surface became entrained in the leading edge of Wave Puck. Using the velocity from this drifter we can get a good idea of how when and where oil particles will make landfall if they were to get entrained in an internal wave packet. We can also use the velocity from the drifter that was on the surface in Wave Maximus. This drifter was not moving in the southwestern direction, so we can get an idea of how oil may be transported without the influence of an internal wave packet. Obviously these are not the only ways that an oil spill could be transported on shore, but by using the data we have from the surface drifters, these are two real possibilities.

A 1,000,000 L oil spill was hypothesized 20 nautical miles northeast of Scituate. The analysis of the hypothetical transport of the oil is shown in Figure 26. If the oil were to be entrained in the leading edge of the wave packet, then it would travel 0.38 m/s in the southwest direction. Then, the oil would make landfall at Scituate, a little more than a day after it was spilled. In his paper, Shanks observes an internal wave packet propagate through an oil spill off the coast of North Carolina (Shanks, 1987). In his study he found that 68% of the oil was found in front of the wave packet, while the rest of the oil was found behind the wave train. Thus, by using this value for the “catching efficiency,” we can estimate that 680,000 L will land at Scituate. However, if the oil was not entrained in a wave packet, then it could travel 0.42 m/s to the west and land 6-½ days later in Boston Harbor. Again, this hypothetical transport is just based on the single data set of the surface drifter in Wave Maximus and may not reflect general trend of transport on the surface of Mass Bay. Just by considering the effect of the internal waves we were able to
come up with drastically different conclusions on where and when the oil would make landfall.

**Conclusion**

Previously, internal waves have not been well understood by the scientific community because they are difficult to quantify. They propagate through the top of the water column and can only be tracked by sensitive instruments. Thus, they were usually neglected when oceanographers developed models of different transportation processes. However, with developing technologies, we are able to track these waves and quantify the transport that is associated with them. In doing so, we can make useful predictions about how particles, such as nutrients, organisms, and pollution are transported by the oceanic currents.

**Further Research**

Further research into the effect of the wind and the tidal flow on the transport of the drifter is necessary. For example, if the drifter is deployed for around 12 hours we will be able to subtract the effect of the tidal flow. After 12.4 hours, the ebb tide and the flood tide will cancel each other out, so the total transport will not be affected by these flows. If we also could deploy when the wind was very low, we would be able to observe the transport of the drifter without any influence by the wind. Obviously, it is impossible to ensure that the wind speed on the open ocean will remain low for an extended period of time, but after enough deployments we may be able to get a good data set.

**Acknowledgements**
I would like to thank Jim Lerczak and Kipp Shearman for their guidance and patience while mentoring this summer. Also, I would like to thank CIOSS for funding my internship at COAS. The crew of the R/V Cape Hatteras was essential for the success of the research cruise. Finally, I would like to thank Kaplan Yalcin for organizing the REU program and getting all the logistics sorted out.

References


<http://fvcom.smast.umassd.edu/research_projects/MassBay/index>


Figures

Figure 1. Pictures 1-4 show the depression in the gradient forming as the tidal current moves from left to right. Pictures 5-8 show the wave propagating on the bank from right to left as the tidal current reverses.

Figure 1 (Pictures 1-4):
Figure 1 (Pictures 5-8):
Figure 2. Irregular bathymetry across seafloor in Massachusetts Bay along NE transect line. Ridge at right is Stellwagen Bank. (Lerczak, 2008)

Figure 4a: Horizontal current profiles at 10 and 44 mab (vertical lines are mentioned in text and occur at the same time in figure 4b).
Figure 4b: Vertical current profile at 15 mab

Figure 5: Currents in an idealized internal wave
Figure 6: Timing of internal wave relative to previous high tide

Figure 7: Timing of high tide relative to previous high tide
Figure 8: Correlation between tidal amplitude and arrival time
Figure 9: Correlation between differences in tidal amplitude and differences in arrival times of internal waves.

Figure 10: Estimated total transport over duration of experiment.
Figure 11: Variations in transport per internal wave packet

Figure 12: Estimated total transport over duration of experiment using Runge-Kutta integration method
Figure 13: Determining the correct settings for the GPS devices on the moorings. The solid black line represents the maximum amount of battery that could be used, while the three dotted lines represent the theoretical battery power that would be used for each different setting. The solid lines represent the accuracy of each setting.

![Dependence of Hold-Off Time on GPS](image)

Figure 14: Determining the correct settings for the GPS devices on the drifter. The solid black line represents the maximum amount of battery that could be used, while the three dotted lines represent the theoretical battery power that would be used for each different setting. The solid lines represent the accuracy of each setting.
Figure 15. Map showing Massachusetts Bay and Stellwagen Bank. Blue dots represent proposed mooring placements. Red dots represent existing mooring sites. Blue line is the transect line that the R/V Cape Hatteras followed. (Lerczak, 2008)
Figure 16: Summary of drifter deployments on DyeWaves08.

<table>
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<th>Wave Name</th>
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<th>Drifters Deployed</th>
<th>Depth Drogued</th>
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<th>Total Transport v (m/s)</th>
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<td></td>
<td>Holy Sock-Red</td>
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Plymouth Harbor
Stellwagen Bank
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Figure 17: The transport lines for all 8 drifters in the ocean using GPS coordinates.

![GPS Positions of All Drogues While In Ocean](image)

Figure 18: The relative positions of the drifters while in ocean using displacement.
Figure 19: The transport velocity of each drifter based on its depth drogued under the surface of the ocean.
Figure 20: The transport lines for all 8 drifters while in the internal wave packets.

Figure 21: The relative positions of the drifters while in internal wave packets using displacement.
Figure 22: The transport velocities of the drifters while in the internal wave packets.

Figure 23: Wind data taken from Buoy 44013 during cruise dates.
Figure 24: The magnitude of the wind speed over the duration of the cruise.
Figure 25: Vector-field of near-surface currents for Mass Bay approximately 3 hours after high tide (Courtesy of Chen, S).

Figure 26: Calculations of transport based on hypothetical oil spill.
<table>
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<tr>
<th>Variables</th>
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