Bodega Harbor Circulation Study
Final Report
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Prepared by:
Linda Rasmussen, John Largier, Melissa Carter
Scripps Institution of Oceanography
University of California, San Diego

Presented to:
Steven Morgan
Bodega Marine Laboratory
University of California, Davis

Contents

The following agencies and individuals provided assistance with data collection, analysis or other operational logistics during the field program undertaken in this study:

Bodega Marine Laboratory, UC Davis
Sonoma County Department of Health Services, Environmental Health Division
North Coast Regional Water Quality Control Board
United States Coast Guard
Spud Point Marina, Bodega Harbor
Dragonfly Aviation
Dr. Linden Clarke, SIO/UCSD
Ron Alvestal

I. Introduction

Figure 1. Campbell Cove at entrance to Bodega Harbor.

Water quality sampling by the Sonoma County Department of Health Services is routinely conducted on county beaches to assess health risks and assure public access to clean beaches. For several years these tests have shown intermittently high levels of bacterial contamination at Campbell Cove State Park in Bodega Harbor, particularly in the autumn months, requiring closures of this recreational beach. To help determine possible sources of the contamination, Scripps Institution of Oceanography (UC San Diego) , in collaboration with Bodega Marine Laboratory (UC Davis), conducted a study of the harbor circulation during the spring and fall of 2003. The primary objectives of the study were to 1) measure current speed and direction in the harbor over different tidal phases; 2) measure movement and dispersion of inert dye tracers introduced into the harbor as proxies for contaminated waters; 3) conduct a thorough survey of temperature, salinity and density in harbor water for use in determining the overall structure of this water body and how it varies over tidal and seasonal cycles. The data collected during the study can provide information on the potential for contamination to be transported, disperse or accumulate to or from different regions of the harbor. Information about flow rates within the harbor have also been supplemented with data collected on water properties and currents outside the mouth of the harbor. Together these can help to determine the probability of outside bay water contributing to contamination within the harbor. A summary of study findings and detailed results are presented in this report.

I. Summary of Bodega Harbor Circulation

Several major features of circulation within Bodega Harbor that could influence contaminant transport and retention may be inferred from the data collected during the Spring and Fall surveys.

- Current data from acoustic doppler current profiling units (ADCP's) in both the front and rear of the harbor show velocities that are constant throughout the water column, enabling a large amount of exchange between the bay outside and harbor water. The flow velocities are about two times greater near Campbell Cove than at the rear of the harbor, providing even more volume exchange in that area.
- Temperature surveys of the harbor by CTD casts during different tidal phases showed a large intrusion of cold bay water during flood tides that affected water properties all the way to the rear of the harbor. Likewise, during ebb tides, surface-warmed rear harbor water was able to flow out to the mouth of the channel within one ebb tide. This suggests that there is a very large degree of flushing of the harbor by bay water during each tidal cycle.
- Tidal flushing is particularly important in the vicinity of Campbell Cove where consistent, vertically uniform tidal flows have the effect of near total replacement of water in that basin with each tidal cycle.
- Drifters released in the harbor corroborated the CTD and ADCP data, and showed currents transporting surface water in the channel the entire length of the harbor within one tidal cycle.
- Drifters released more than a couple hundred meters outside the harbor were not entrained into the flood tide current entering the harbor.
- Dye release experiments also showed that advective transport within the harbor is quite rapid, particularly within the main channel. Water in the rear marinas and over the tidal flats did not have such high velocity, but drainage did occur over the tidal flats, primarily into the main channel, and dispersion in regions of low current velocity was still significant enough to dilute dye patches to non-visible levels over a tidal cycle. No dye tracers were ever detected more than a single tidal period from their release time (i.e., dilution of at least 10:1 was achieved).
- Some retention of dye was observed near the edges of the Gaffney Point tidal flats and along the eelgrass boundaries of Campbell Cove, but these were also diluted to non-visible levels within one tidal cycle.

The implications of these findings for contaminant transport in Bodega Harbor should be addressed collaboratively in conjunction with studies done concurrently on bacterial levels and sources in the area. This having been said, we can make some general comments about the possibility of transport to Campbell Cove from candidate source regions: inner harbor, bay waters, tidal flats, cove itself.

- ***Back Harbor (Spud Point Marina, Porto Bodega, etc.)***
  Results from dye releases, drifters, ADCP current measurements, and CTD surveys all indicate that there is not rapid advection out of the marina and that the connection between the marinas and the main channel is weak. Waters that did enter the main channel from this area during our experiments had undergone significant dilution. Once in the main channel, these waters are flushed rapidly through the harbor with each tidal cycle. It is therefore unlikely that the back harbor area is a source of high concentrations at Campbell Cove, without simultaneous contamination at other locations.

- ***Bodega Bay*** (outside mouth of harbor, including Bodega Rock, Doran Beach)
  Drifter experiments indicated that the withdrawal zone for bay water entering the harbor during flood tide is small and localized, extending not more than a few hundred meters offshore from the harbor mouth. It is unlikely that contamination from sources beyond this zone (i.e., seals at Bodega Rock, boats in the bay) would have an impact on Campbell Cove, particularly with the more energetic mixing and dilution that occurs in the bay as opposed to the harbor.

  However, nearshore waters may be entrained from distances greater than a few hundred meters as they are moved past the harbor mouth by ambient circulation. For example, under westward flows past the mouth (e.g., fall study), pollutants introduced along Doran Beach may move alongshore and then into the mouth. Likewise, under eastward flow (e.g., spring study), pollutants introduced along Bodega Head may be entrained by tidal flows into the mouth.

- ***Gaffney Point Tidal Flats***
  Dye releases over the tidal flats during ebb tide showed transport mainly in the direction of the central channel. However, some dye along the southwestern side of the flats did move shoreward and toward Campbell Cove en route to the main channel. However, the dye we observed was not visible more than 4 hours after its release, although some low concentrations may persist. Specifically, if water draining from the flats became entrained in the boundary layer in the nearshore zone, it could persist longer than we observed. This could occur particularly if a source was nearer to the shore than the dye releases, or if there was a long-lived or continuous source that could be introduced repeatedly over many tidal cycles.

- ***Campbell Cove***
  Campbell Cove itself could be a source for contaminants found there. As with the tidal flats, dye released near shore had a tendency to hug the shoreline, dispersing alongshore but not offshore. Also, dye released in the center of the cove at flood tide dispersed more or less radially, and some became entrapped in the eelgrass nearshore while the main patch advected up the channel. If there was a contaminant source at or near the shoreline it is possible that contaminants could persist in the boundary layer for longer than one tidal cycle (although we did not observe this with our dye). One scenario in which this could occur is if there were a persistent source along the shoreline that introduced contaminants steadily; then, the slow flushing of these ankle-deep waters would allow them to persist or accumulate over time.

III. Study Results

Data were collected and field experiments conducted in Bodega Harbor and the adjacent bay during the spring and fall of 2003, 14-23 May and 13-20 October.

A. Current Velocity & Tides

Moorings with bottom-mounted acoustic doppler current profilers (ADCP) were deployed near the mouth and the rear of the harbor in Spring 2003, and at the mouth in Fall 2003 (Figure 2). The ADCP units provide continuous records of the current velocity through the entire water column at the deployment location. The ADCP units were deployed for 4-5 weeks each season, concurrent with the field studies. ADCP units measure both current velocity and water depth, and thus provide good measures of both current and tidal fluctuations.

The ADCP figures in this section show the current velocity at individual mooring sites. The vertical axis is water depth, measured in meters of seawater above bottom. The horizontal axis is time. Changes in water depth over time due to tidal fluctuation can be seen along the top of the plots. Colors indicate the current speed. All plots shown are for the major, north-south component of the current velocity, corresponding to the major orientation of the harbor channel. Velocities > 0 are northward in direction, shown in yellow to red. Velocities < 0 are southward in direction and are shown in turquoise (cyan) to dark blue. Velocities near zero appear in the green range. The major feature immediately visible in the plots is the north-south change in current direction over the semi-diurnal tidal cycles (i.e., cyclic shift from red (northward, flood tide) to blue (southward, ebb tide).

Full records for all of the deployments are shown in Figure 3 (Spring) and Figure 4 (Fall). The spring data shows that velocities near the entrance to the harbor (including Campbell Cove) are typically about double those in the rear of the harbor, especially during strong spring tides (e.g., around 6/15). Velocities during the spring season ranged from ±40 cm/s during neap tides to ±80 cm/s during spring tides near Campbell Cove (positive = northward, negative = southward) (Figure 5). During the fall season (Figure 6 and Figure 7) velocity ranges were similar.

One feature that is important in considerations of contaminant transport within the harbor is the lack of vertical shear. Many bay and estuary systems have vertical stratification due to the difference in temperature and salinity between the outside ocean and interior waters. The stratification can result in flows of different speeds or even different direction at different depths. The velocity profiles in Bodega Harbor show water within the channel moving uniformly from top to bottom at fairly rapid flow rates, indicating a large throughput through the system. There is some minor stratification in the flow at the beginning of ebb tide on some days (see detailed view of single day cycles in Figure 8) but they are relatively brief. This suggests that there is both a large volume exchange between the bay and harbor, and a low residence time within the harbor. Although the flow rates at the rear of the channel are lower than at the mouth, the flow there is also non-stratified. Lower flow rates are probably due to the larger drainage area (tidal flats on either side) over which water enters and leaves the channel during tidal changes; this flow is then concentrated into the much narrower region at the mouth of the harbor.

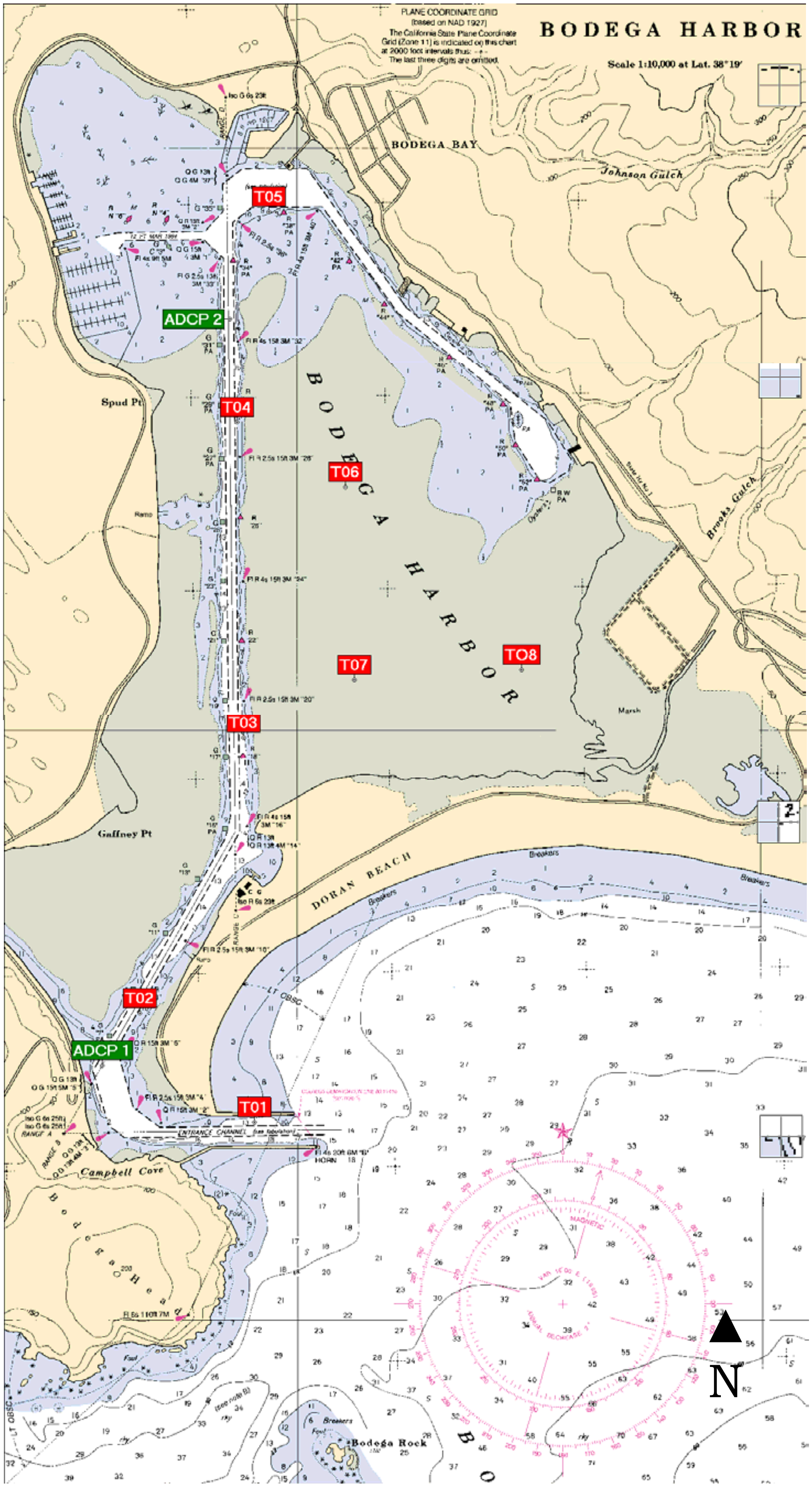


Figure 2. Bodega Harbor. Moored instrument positions are shown for current profilers (ADCP's, green) and temperature sensors (red).

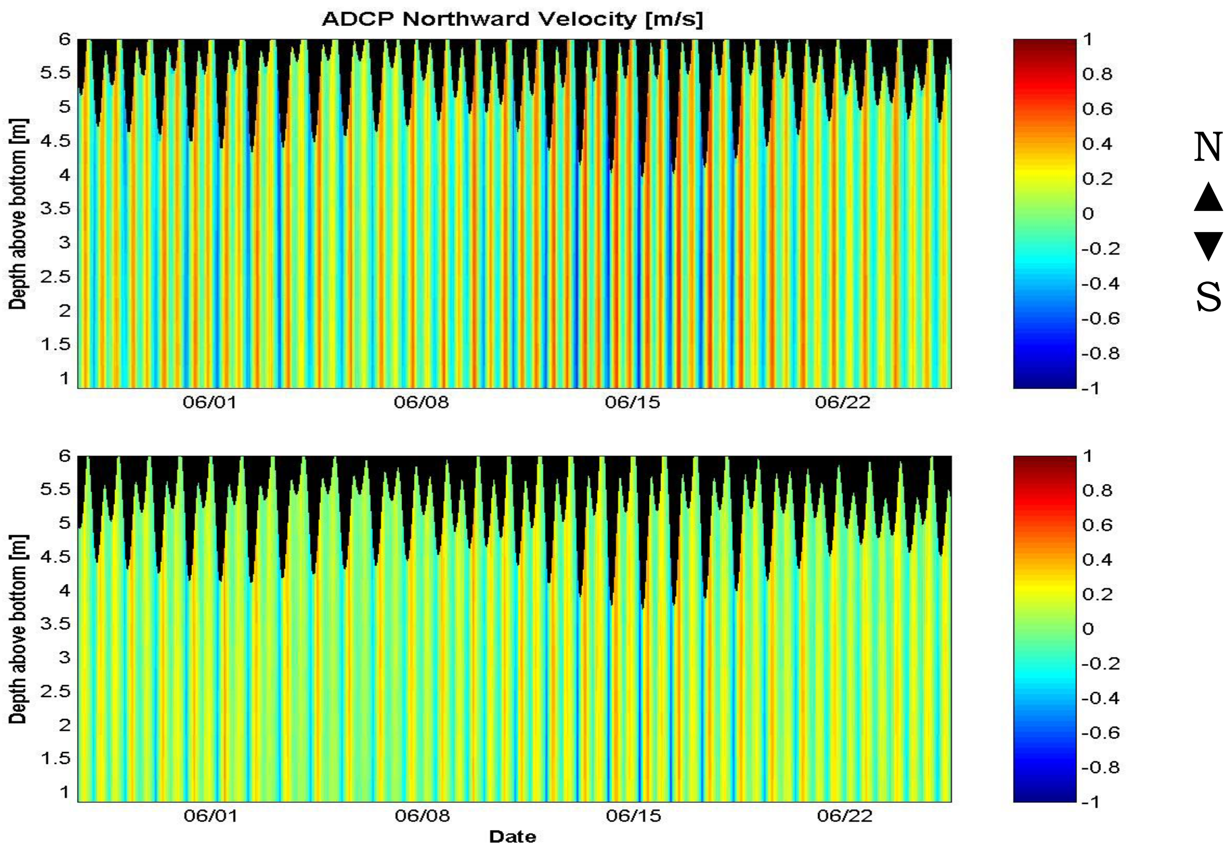


Figure 3. Along-channel current velocity and tides over a one-month period at Campbell Cove (top) and Spud Point (bottom), Spring 2003. The vertical axis is depth of the water column from the channel bottom. Positive velocities (yellow-red) are northward (into or up channel) and negative velocities (cyan-blue) are southward (out of or down channel).

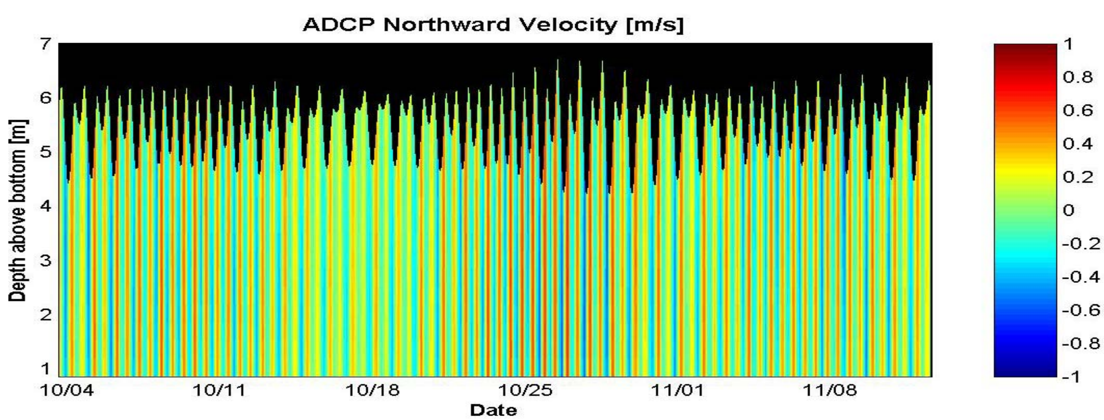


Figure 4. Along-channel current velocity and tides over a five-week period at Campbell Cove, Fall 2003. The vertical axis is depth of the water column from the channel bottom. Positive velocities (yellow-red) are northward (into or up channel) and negative velocities (cyan-blue) are southward (out of or down channel).

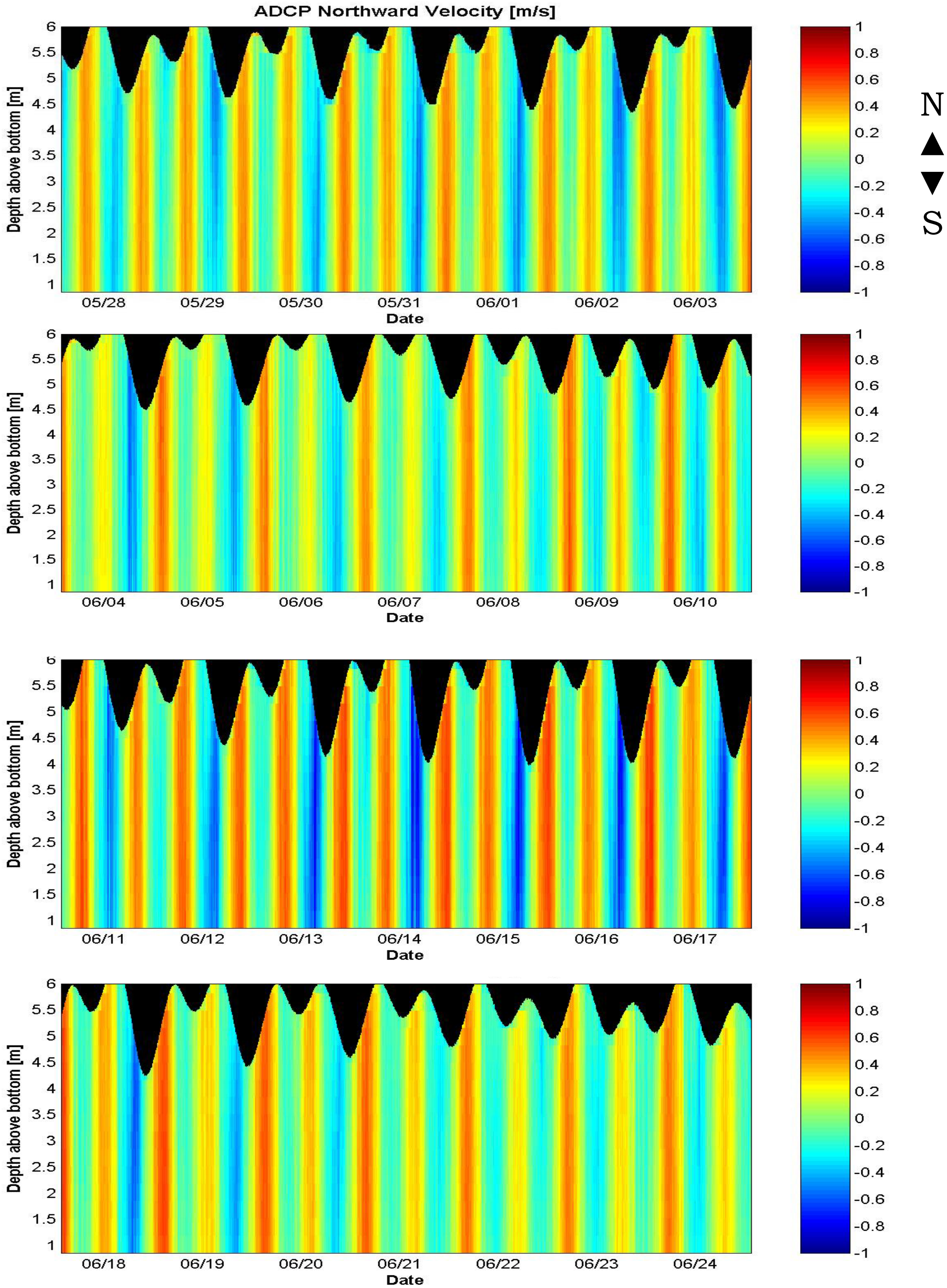


Figure 5. Along-channel current velocity and tides, Campbell Cove , Spring 2003. Positive velocities (yellow-red) are northward (into or up channel) and negative velocities (cyan-blue) are southward (out of or down channel).

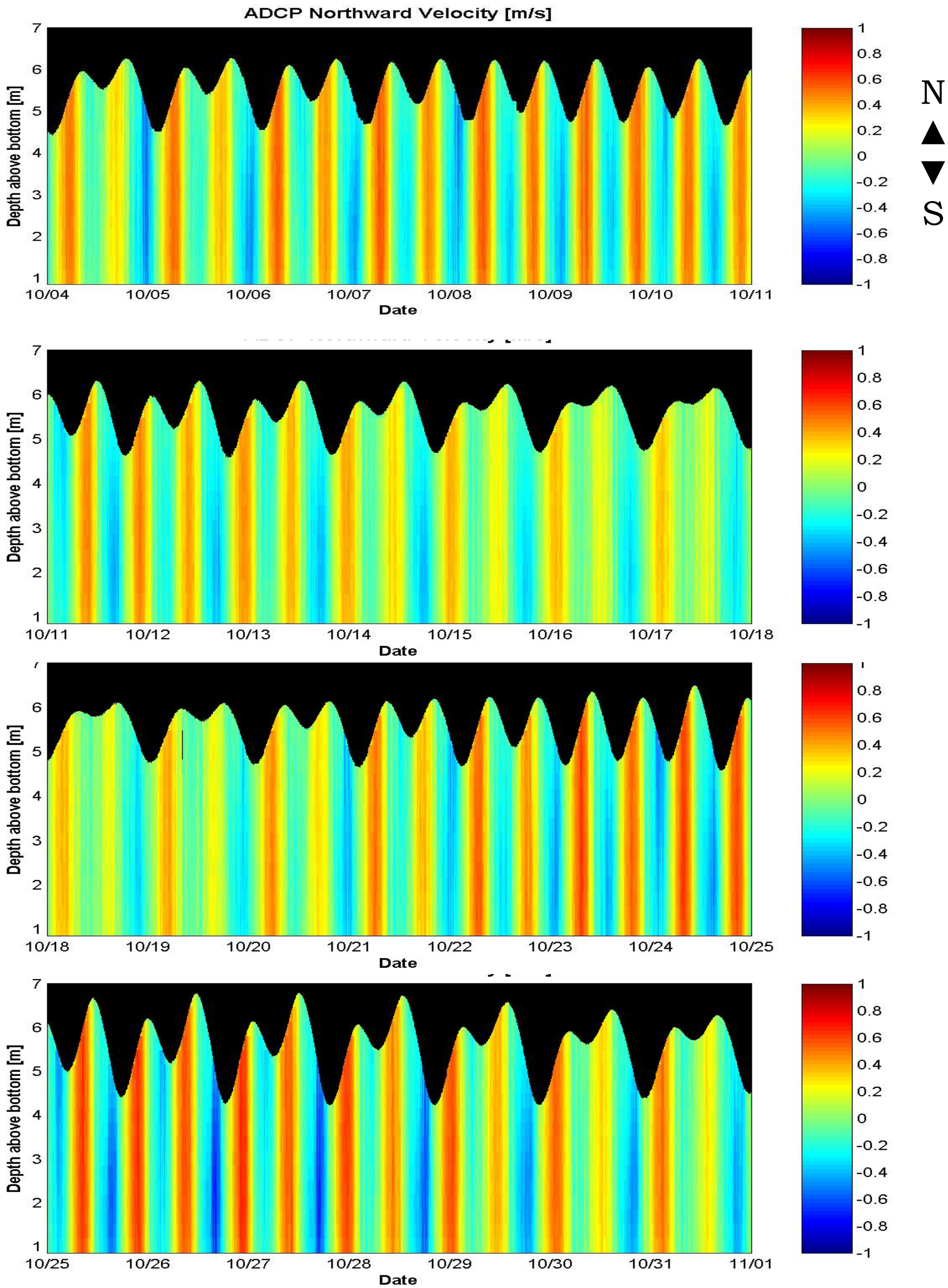


Figure 6. Along-channel current velocity and tides , Campbell Cove, Fall 2003. Positive velocities (yellow-red) are northward (into or up channel) and negative velocities (cyan-blue) are southward (out of or down channel).

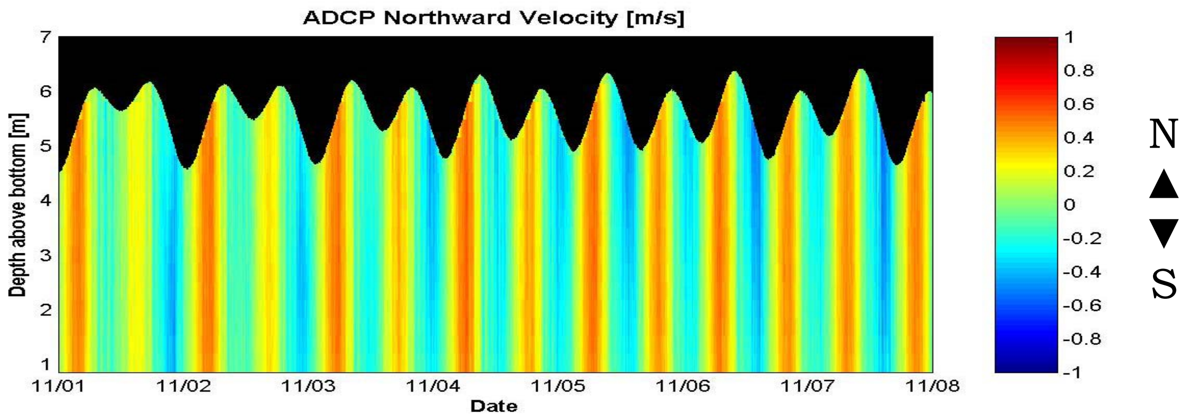


Figure 7. Along-channel current velocity and tides, Campbell Cove, Fall 2003 (cont.)

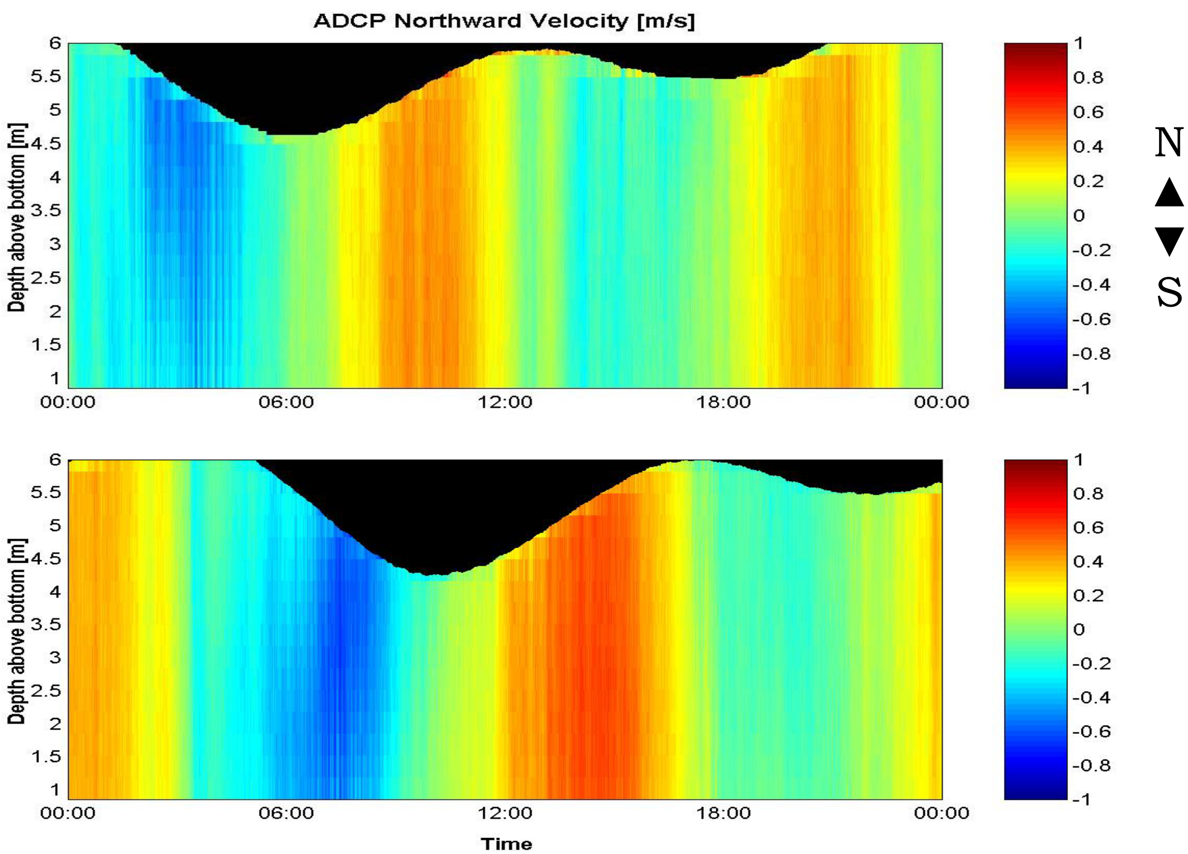


Figure 8. Along-channel current velocity and tides, Campbell Cove. Top: 29-30 May 2003, Bottom: 18-19 June 2003. Note minor vertical differences in flow rates during early morning ebb tides. Positive velocities (yellow-red) are northward (into or up channel) and negative velocities (cyan-blue) are southward (out of or down channel).

B. Temperature and Salinity Structure

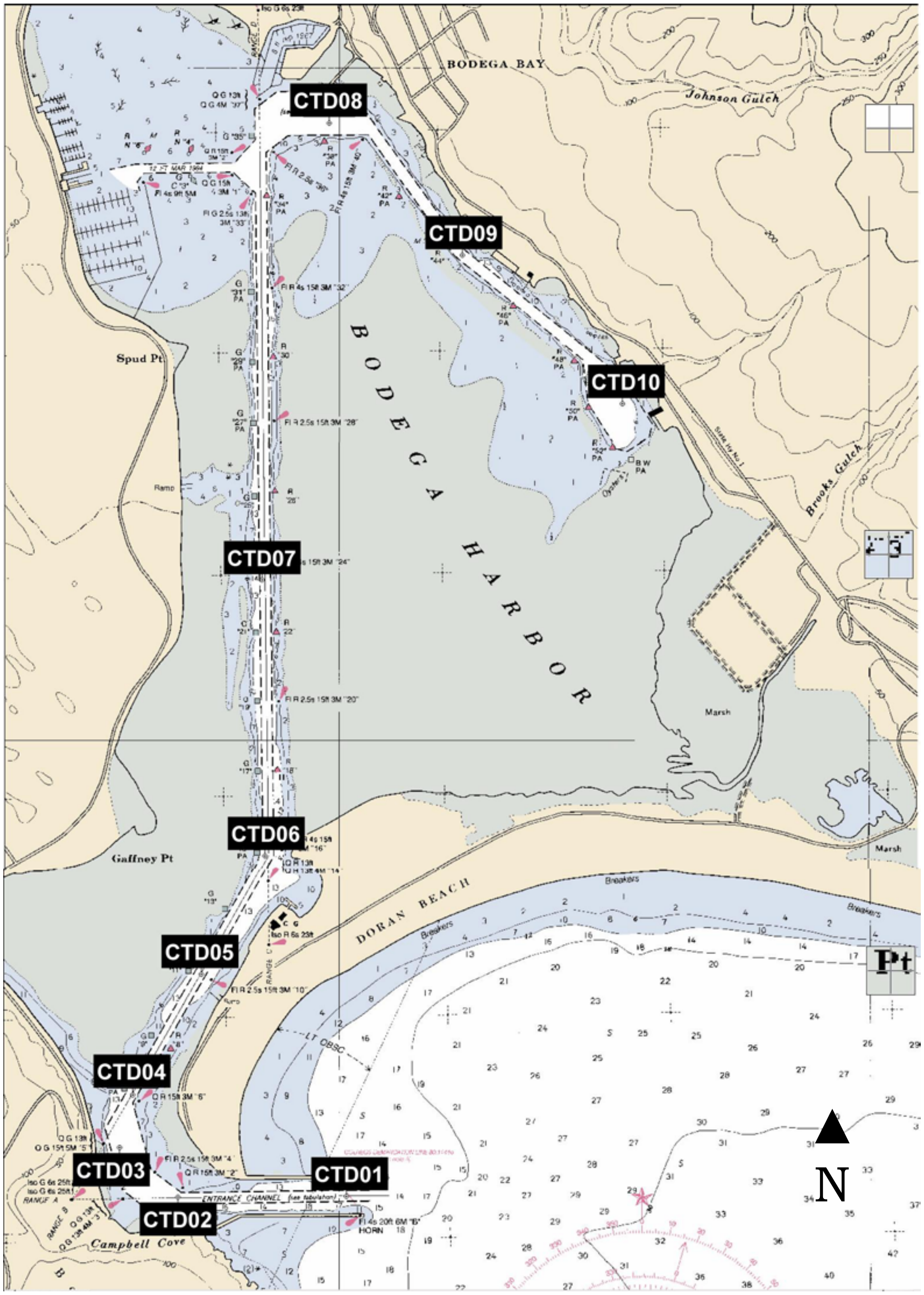


Figure 9. Spring 2003 CTD stations

During both the Spring and Fall field studies four along-channel CTD transects were surveyed on two days over different tidal cycles to provide information on the salinity, temperature and density structure of the harbor. Preliminary analysis of this data indicates a strong tidal influence and heat/volume exchange within the harbor over single tidal cycles. Locations of the CTD stations are shown in Figure 9 (Spring channel surveys) and Figure 13 (Fall channel surveys).

Vertical sections of the temperature, salinity and density of water along the channel for each of the spring surveys are shown in Figure 10 (flood and ebb tide on May 18) and Figure 12 (two phases of flood tide on May 22). The flood tide survey on May 18 shows unstratified 9-10 ºC bay water in the harbor nearly as far as Spud Point (between CTD stations 7 and 8), with some surface warming at the stations in the rear of the harbor (CTD 8,9,10). During the subsequent ebb tide (bottom Figure 10), the inflowing cold bay water has been completely displaced by outflowing warmed rear harbor water all the way to the mouth of the channel. The salinity signature of the "bay water" and "harbor water" is nearly identical, which is another indication that the harbor water is just locally (and recently) warmed bay water.

The survey on May 22 (Figure 10) shows the progression of the flood tide through the harbor. At the top, the bay water is just entering the harbor and has not yet reached the Coast Guard station; the horizontal temperature gradient between the incoming bay water and harbor water is clearly visible between stations 5 and 7. Three hours later into the flood tide, the bay water influence is seen all the way to the north end of the harbor, and temperatures have dropped by 1ºC at the end of the channel. Continuing surface warming in the harbor is evident at the rear stations where 1-2.5 ºC temperature differences occur between the surface and bottom.

The survey period was during a time of smaller tidal ranges which is reflected in the CTD profiles through the harbor (Figure 14 and Figure 16). Bay water temperatures during this period were 11-12 ºC. The temperature profiles through the harbor near the end of a weak flood tide on 16 October (Figure 14, top) still show the intrusion of bay water to the end of the channel, but the weaker flow has allowed more surface warming and stratified conditions to persist throughout the harbor. This particular flood tide occurs after a virtually non-existent ebb tide as well, so there has been little movement of warm rear harbor water out of the channel (see ADCP for 10/16 on Figure 7). Similar conditions occur during the beginning of the weak flood tide of 19 October (Figure 16). This flood tide takes place after a weak ebb tide and surface-warmed water is still evident as far south as the Coast Guard Station (CTD 3). Although the tidal flows are weak during this time, bay water influence is still evident throughout the harbor ($T < 12$ ºC). Uniform ADCP velocities throughout the water column also suggest that vertical temperature differences are the result of immediate surface heating and not of a stratified flow environment. *This is particularly important in the vicinity of Campbell Cove where consistent, vertically uniform tidal flows would have the effect of near total replacement of water in that basin with each tidal cycle.*

Results of the CTD surveys in Bodega Bay outside the harbor mouth are included at the end of this section for comparison of water properties inside and outside the harbor. In general, temperatures in the bay are only weakly stratified during both Spring and Fall surveys, with no strong pycnocline or evidence of upwelling conditions at either time. Water depths and properties 100-500 m from the harbor entrance are virtually identical to those within the channel at Campbell Cove.

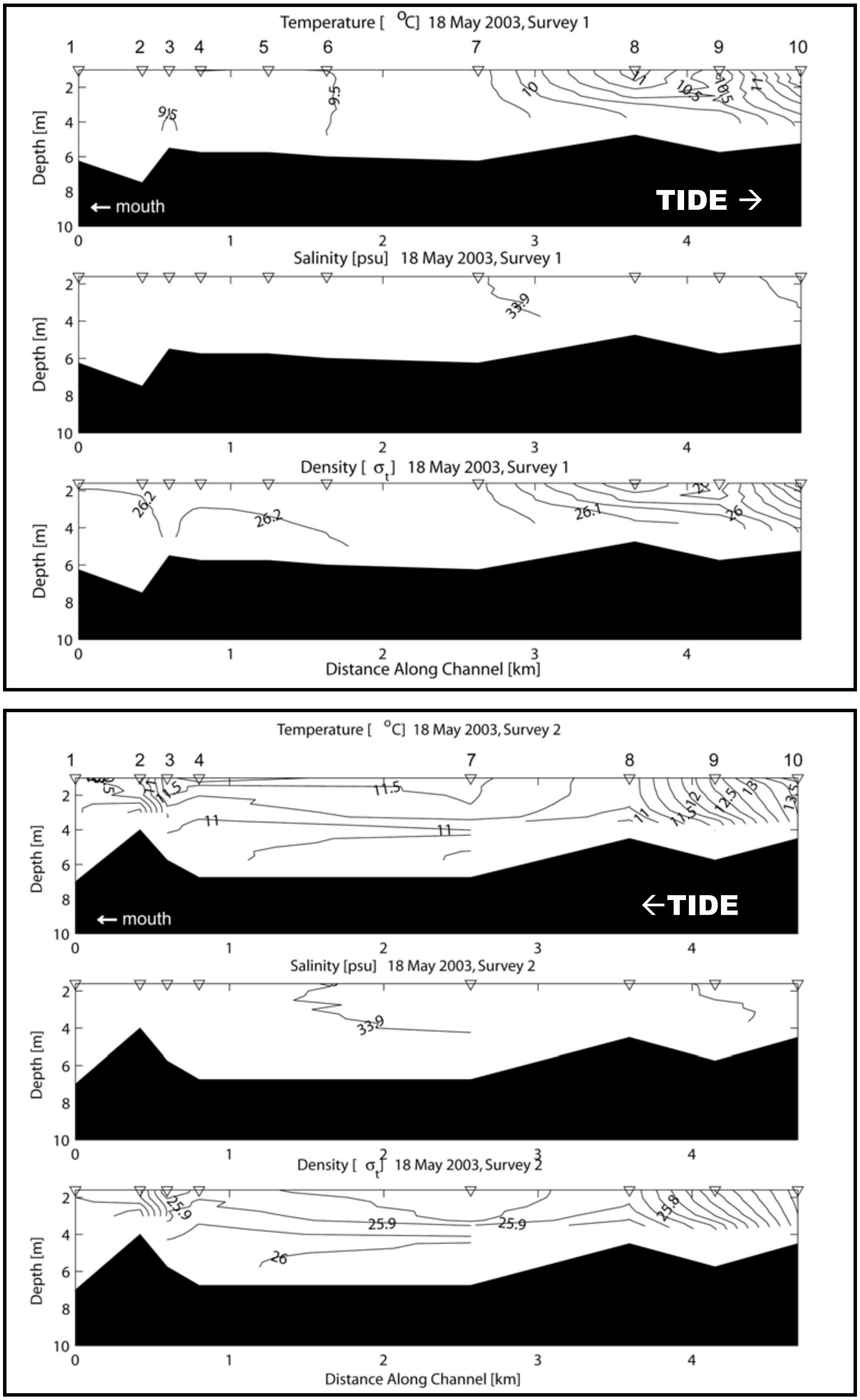
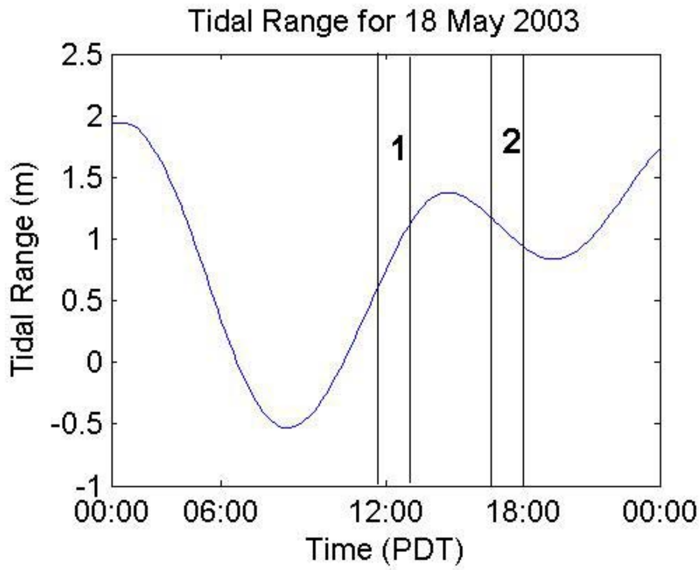


Figure 10. CTD Surveys, 18 May 2003. Top: Flood tide (11:30-13:30), Bottom: Ebb tide (16:00-18:00). Horizontal axis is distance along channel from CTD 1 (mouth) to CTD 10. Station markers (triangles) at top of plots. Well mixed water is visible toward the mouth of the channel during flood tide (stations 1-7), while back harbor water has stronger gradients in temperature stations (8-10). Salinity is fairly uniform througout. and the temperature differences are the cause of the density gradients at the rear channel.



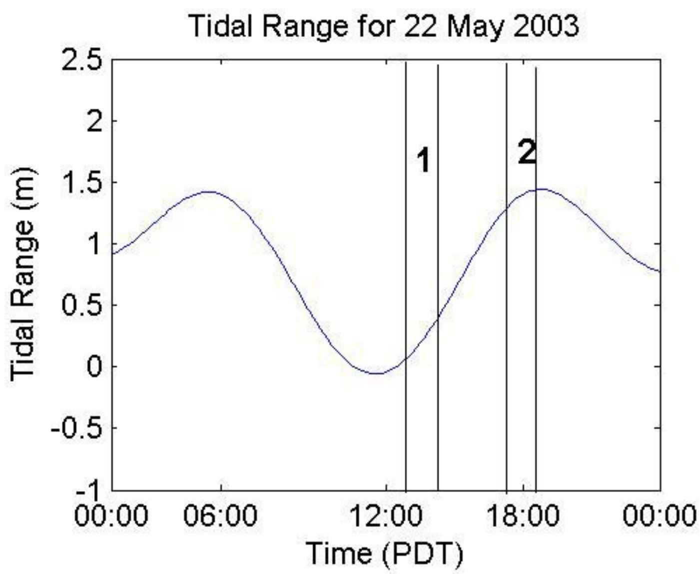


Figure 11. Tidal range during Spring 2003 CTD surveys.

Top: Surveys 1 and 2 on 18 May; Bottom: Surveys 1 and 2 on 22 May.

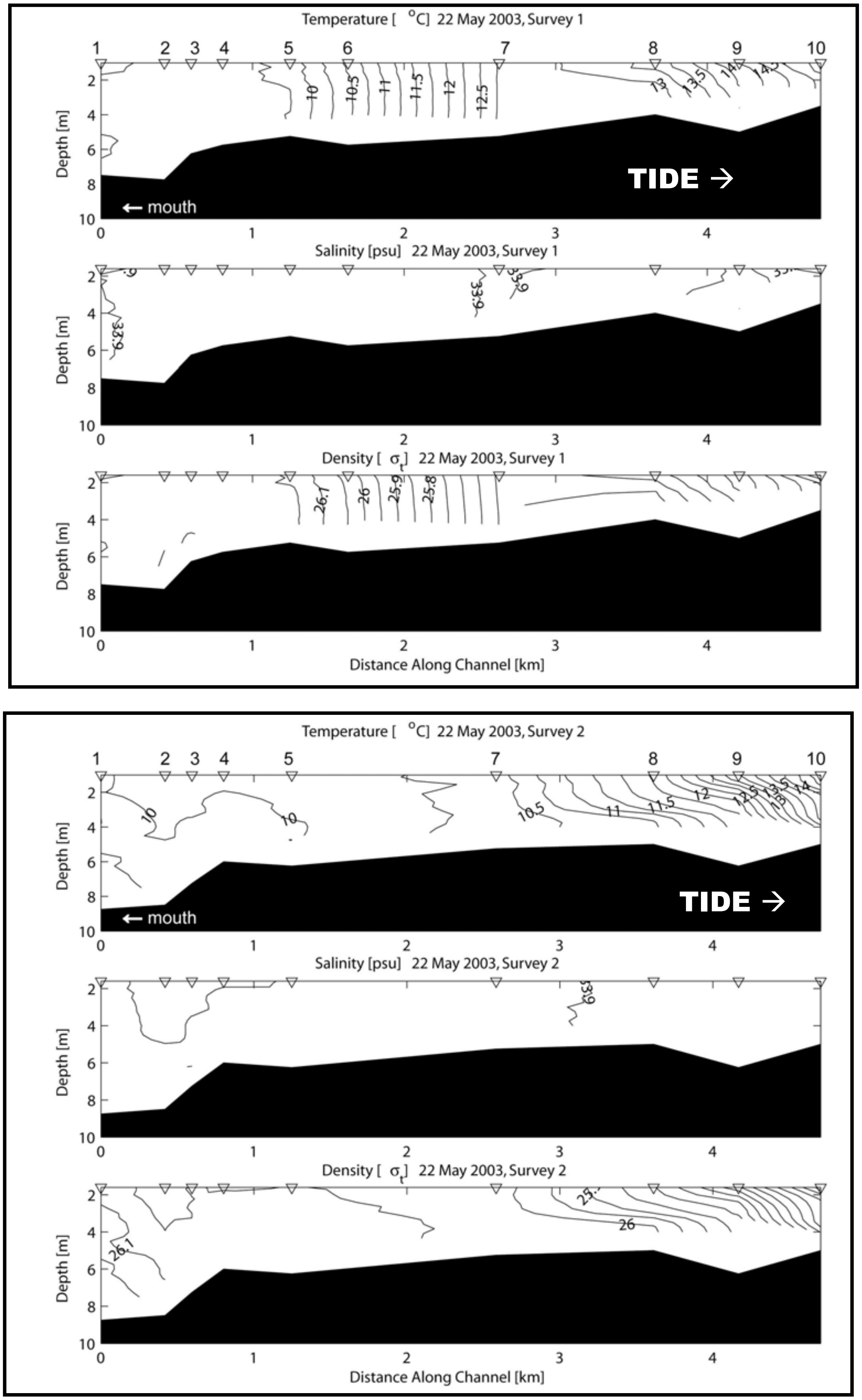


Figure 12. CTD Surveys, 22 May 2003. Top: Mid flood tide (13:15-14:50), Bottom: End flood tide (16:50-18:30). Horizontal axis is distance along the channel from Station 1 to Station 10. Note strong mid-channel temperature gradients during the peak of flood tide (top panel), progressing to the rear of the channel late in the flood tide (bottom, stations 8-10).

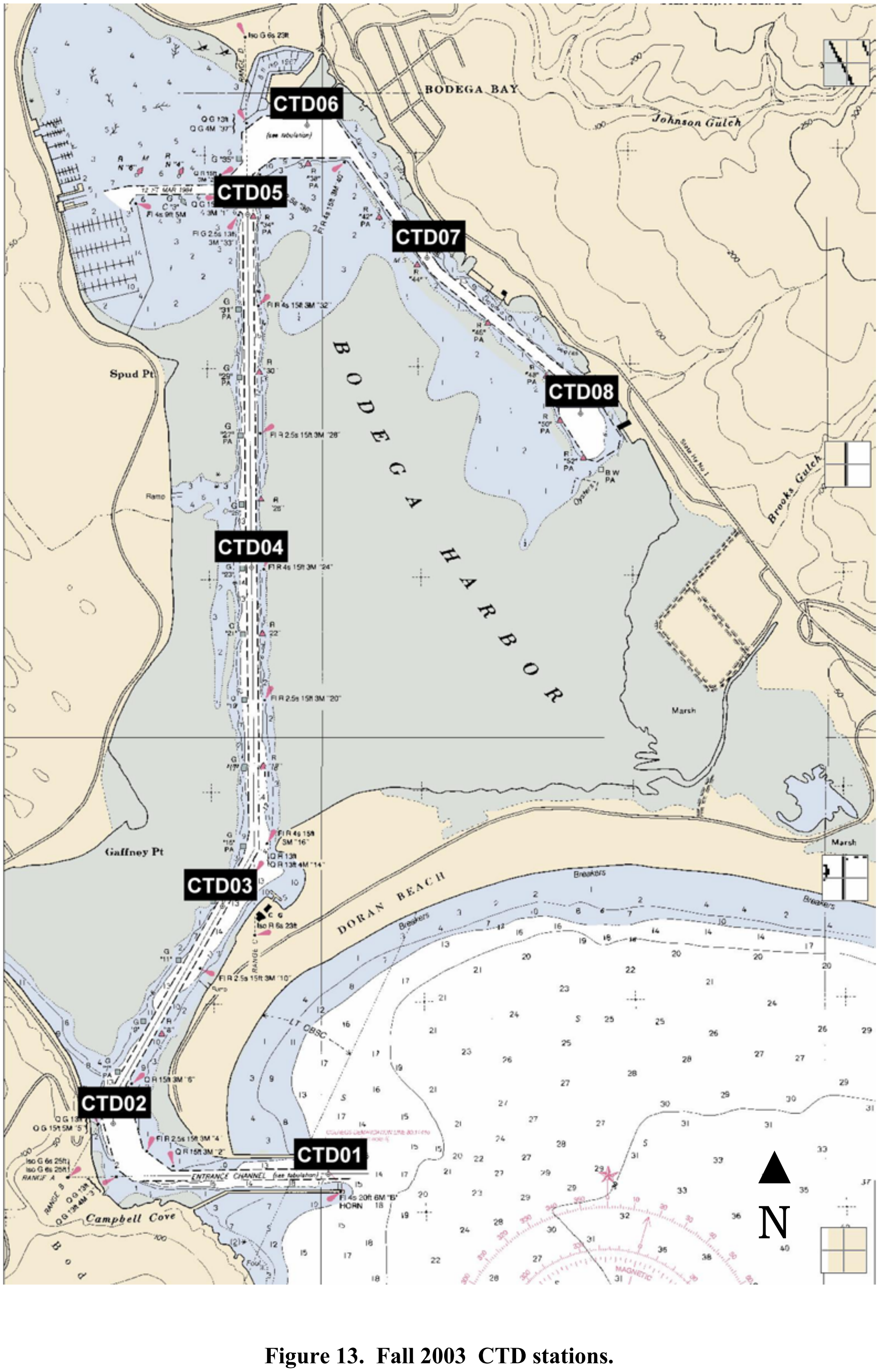
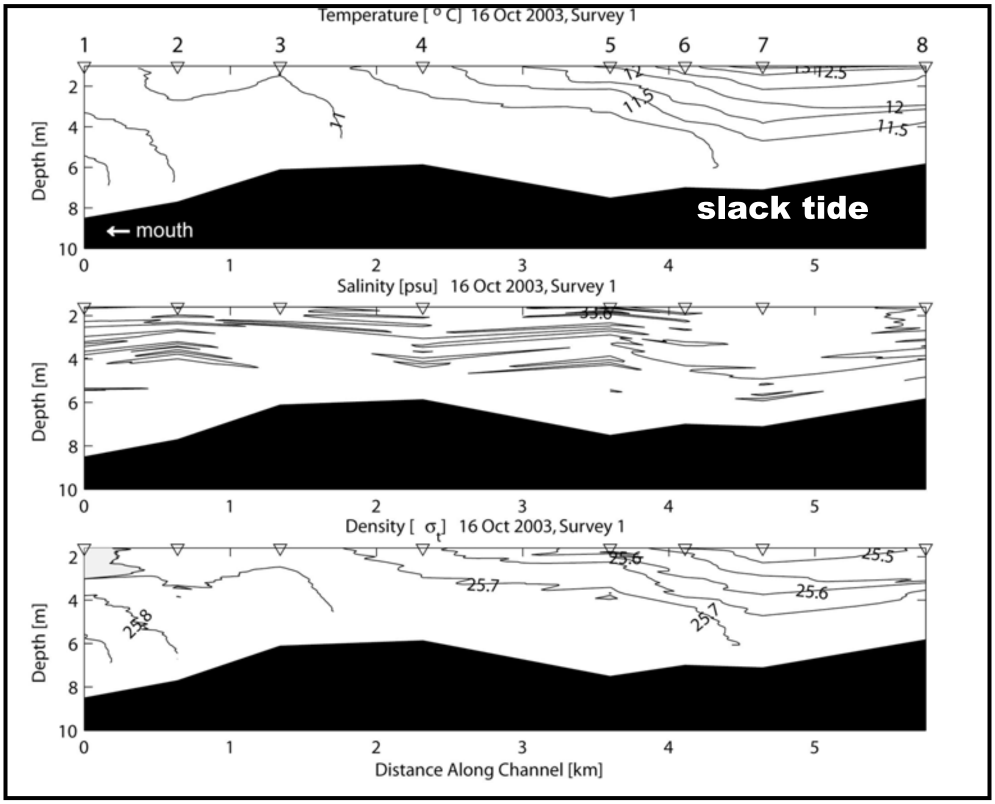


Figure 13. Fall 2003 CTD stations.



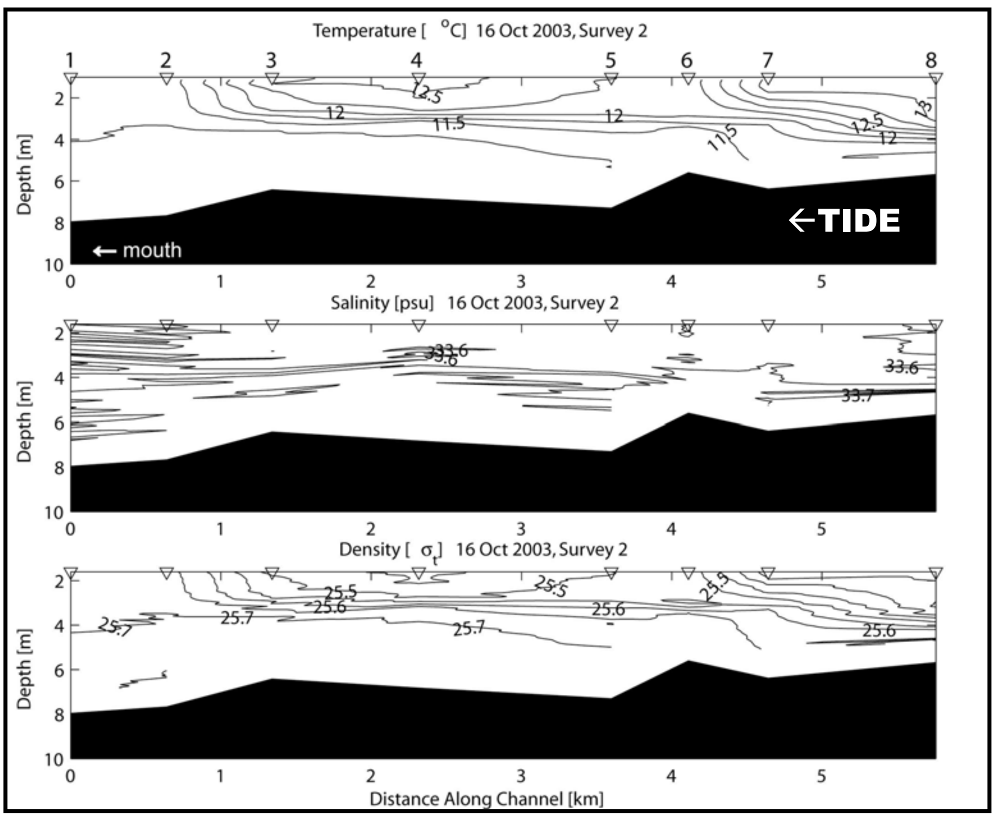
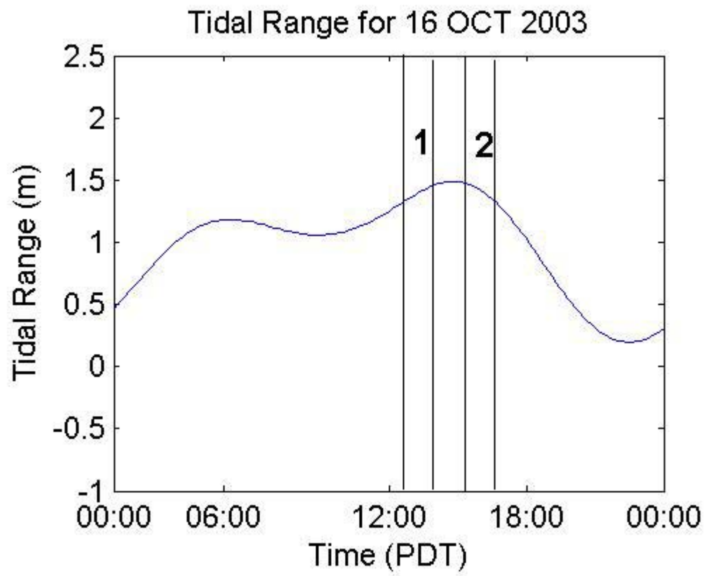


Figure 14. CTD Surveys, 16 October 2003. Top: Weak flood/slack tide (12:50-13:50), Bottom: Ebb tide (15:45-16:25). Horizontal axis is distance along the channel from Station 1 (mouth) to Station 8. Note horizontal stratification from warm back harbor water overlying subsurface water during ebb tide (bottom).



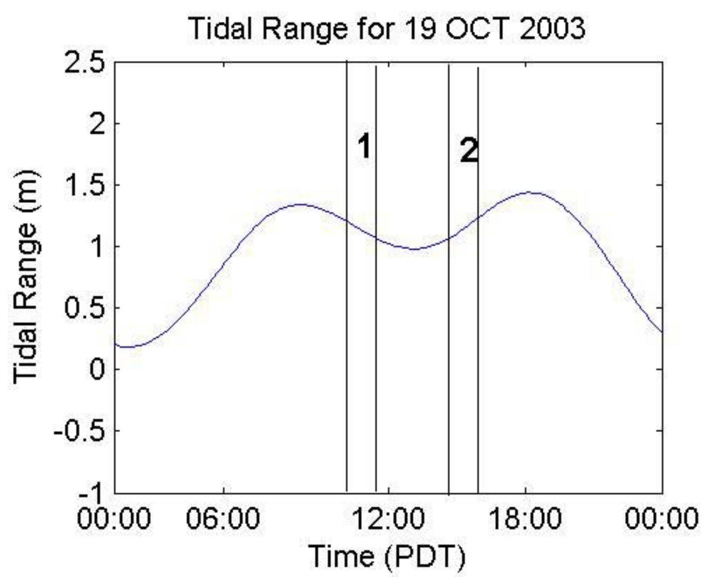


Figure 15. Tidal range during Fall 2003 CTD surveys. Top: surveys 1 and 2 on 16 October; Bottom: surveys 1 and 2 on 19 October.

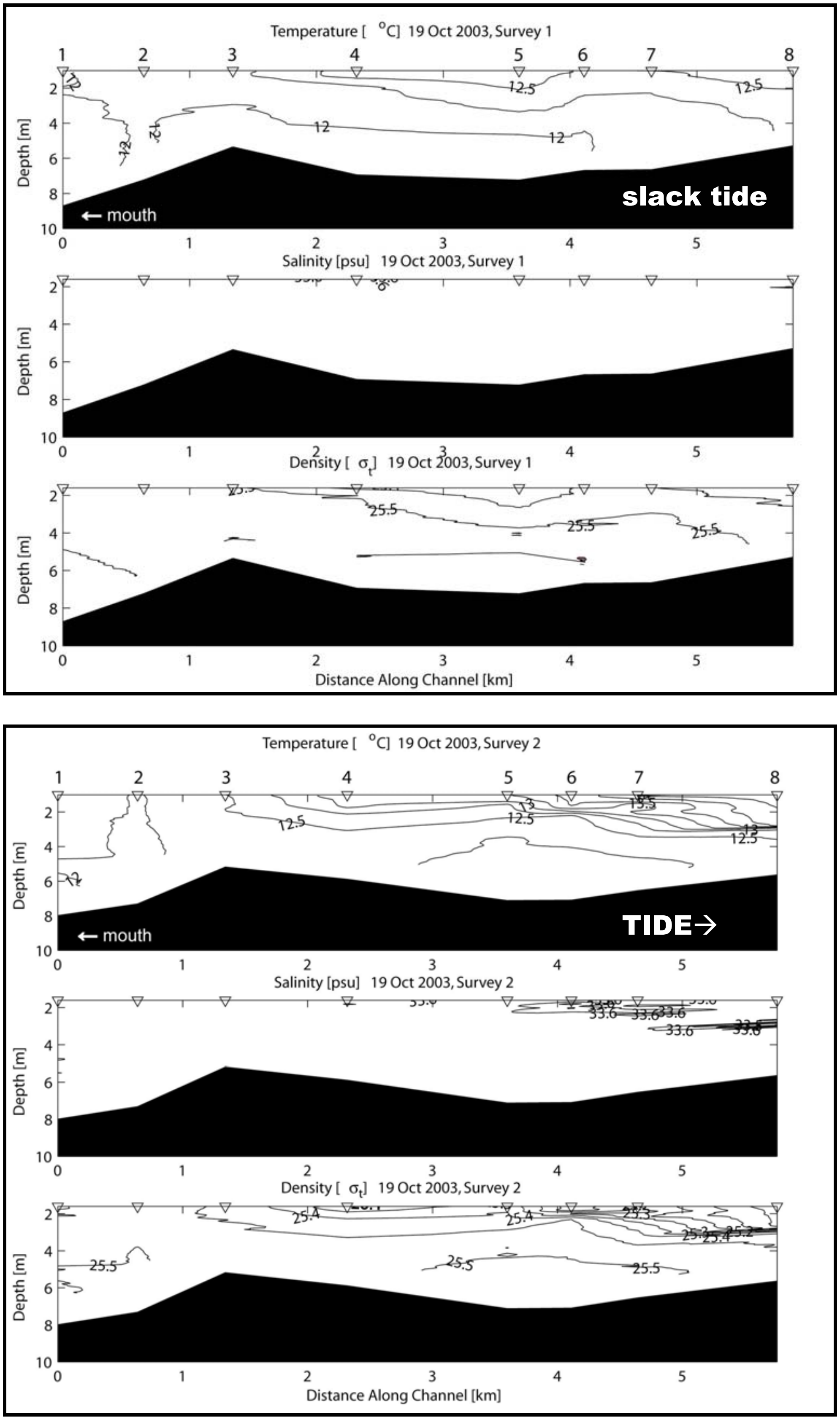


Figure 16. CTD surveys, 19 October 2003. Top: Weak ebb/slack tide (10:45-11:30), Bottom: Weak flood tide (15:00-15:45). Horizontal axis is distance along the channel from Station 1 (mouth) to Station 8. Note lack of strong gradients during these weak tidal cycles.

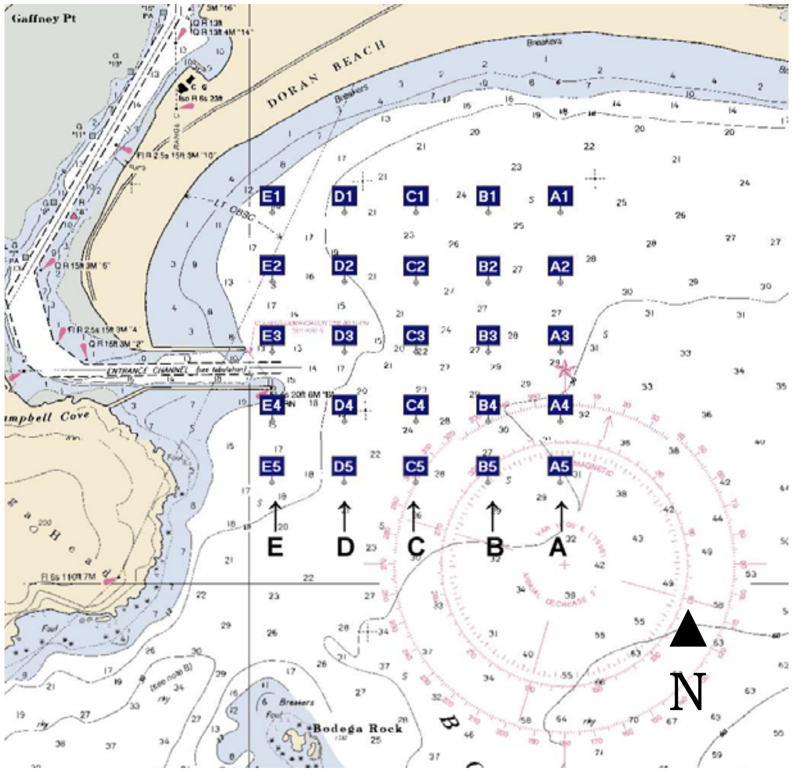


Figure 17. Bay CTD survey, Spring 2003 (19 May, 11:00-14: 00).

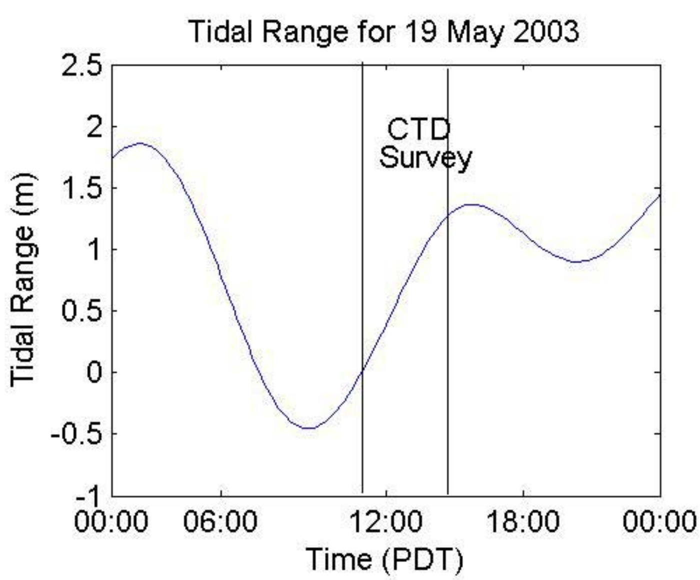


Figure 18. Tidal cycle during Spring 2003 Bay CTD survey.

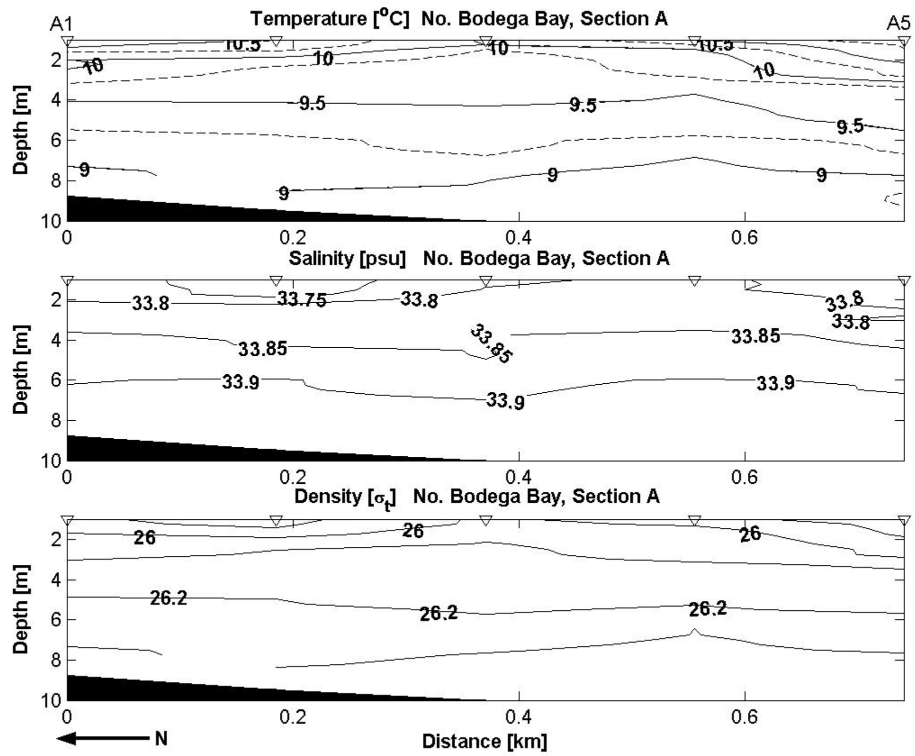


Figure 19. Bay CTD survey, Spring 2003, Section A.

Station locations are indicated by the triangles at top of figures.

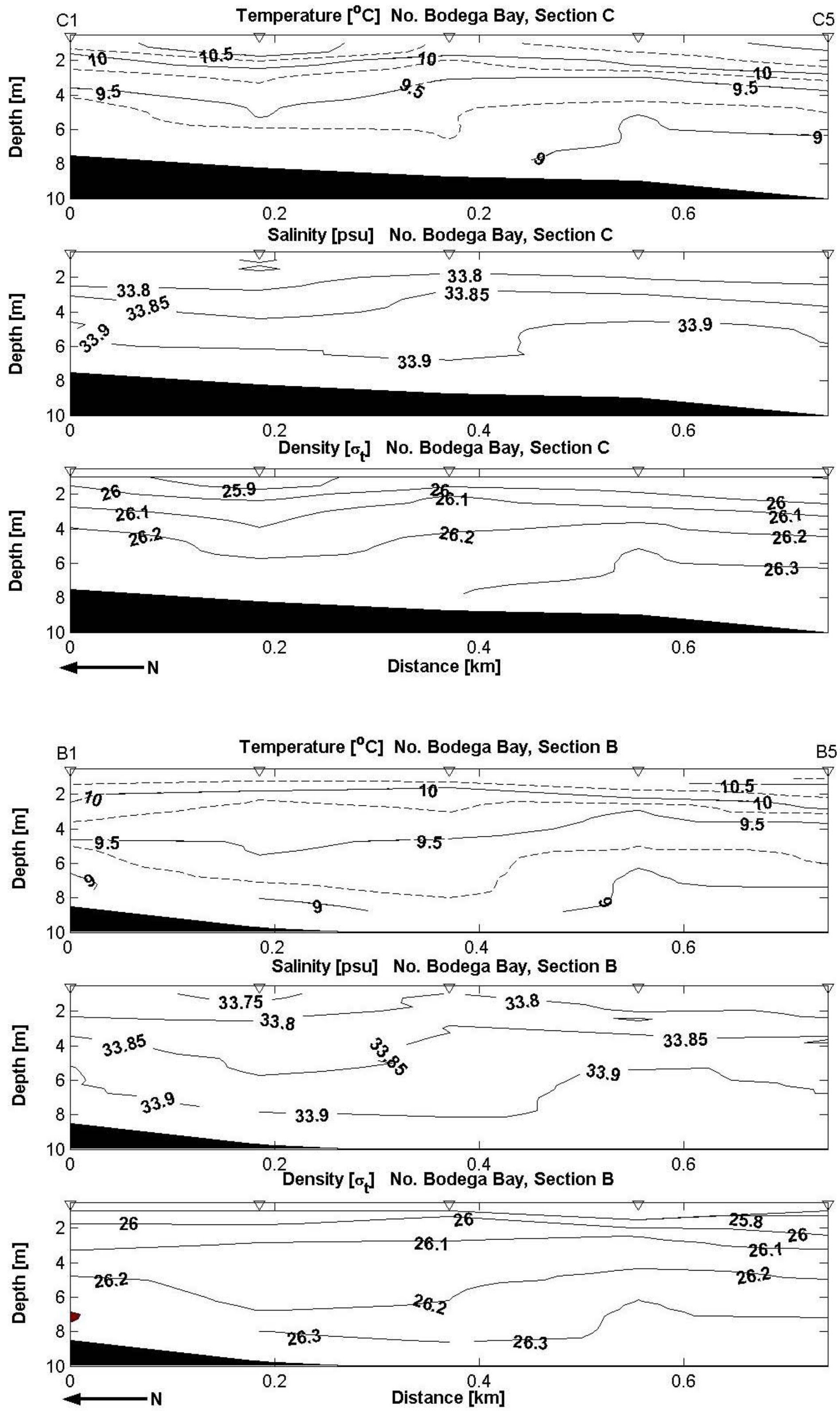


Figure 20. Bay CTD survey, Spring 2003, Sections B and C.
Station locations are indicated by the triangles at top of figures.

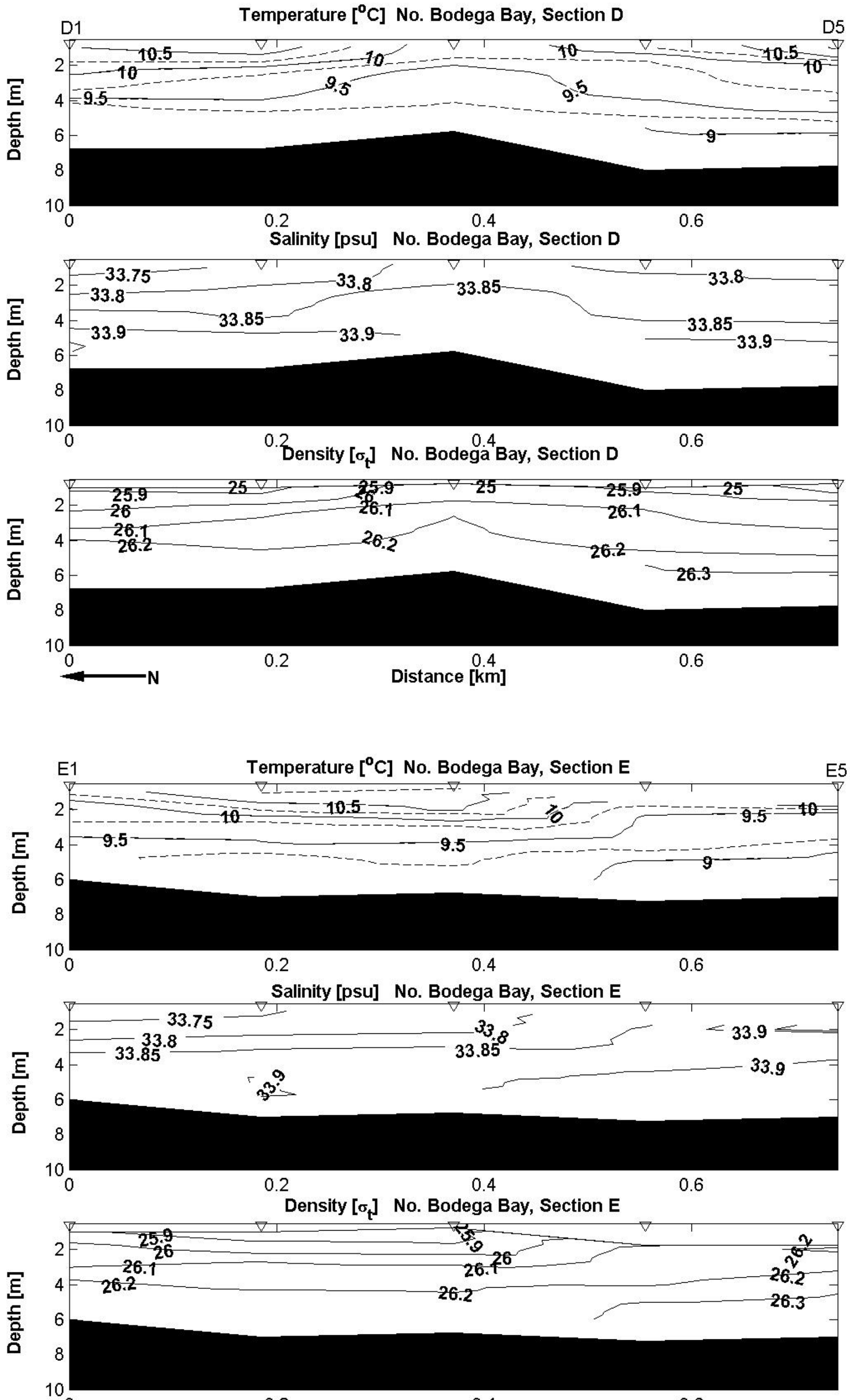


Figure 21. Bay CTD survey, Spring 2003, Sections D and E.

Station locations are indicated by the triangles at top of figures.

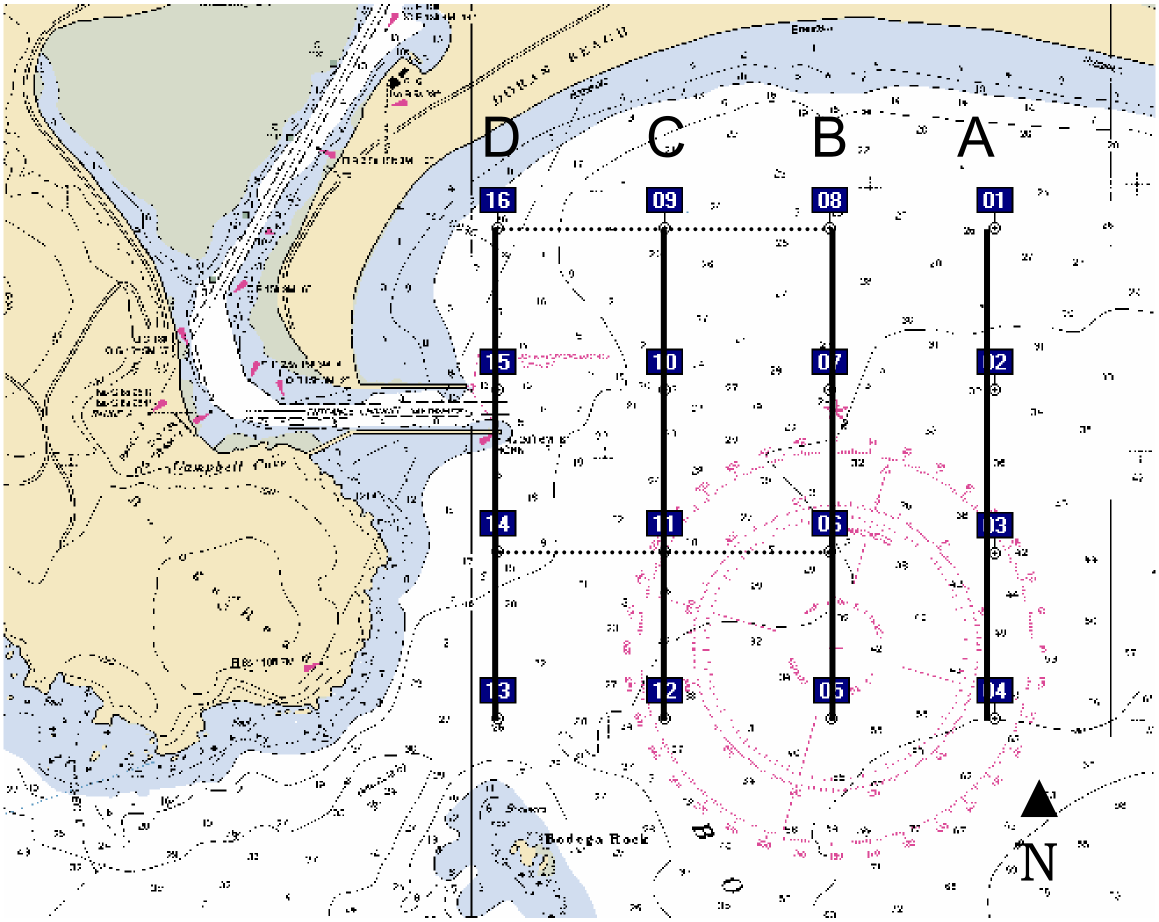


Figure 22. Bay CTD survey, Fall 2003 (17 October, 11:45-13:40). Dashed square indicates boundary of spring survey.

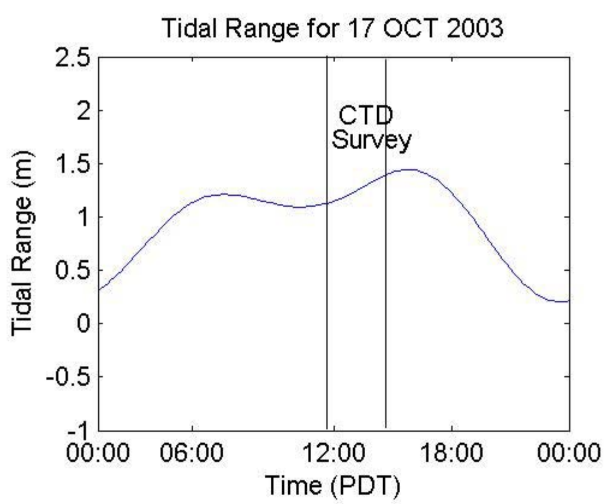


Figure 23. Tidal cycle during Fall 2003 Bay CTD survey.

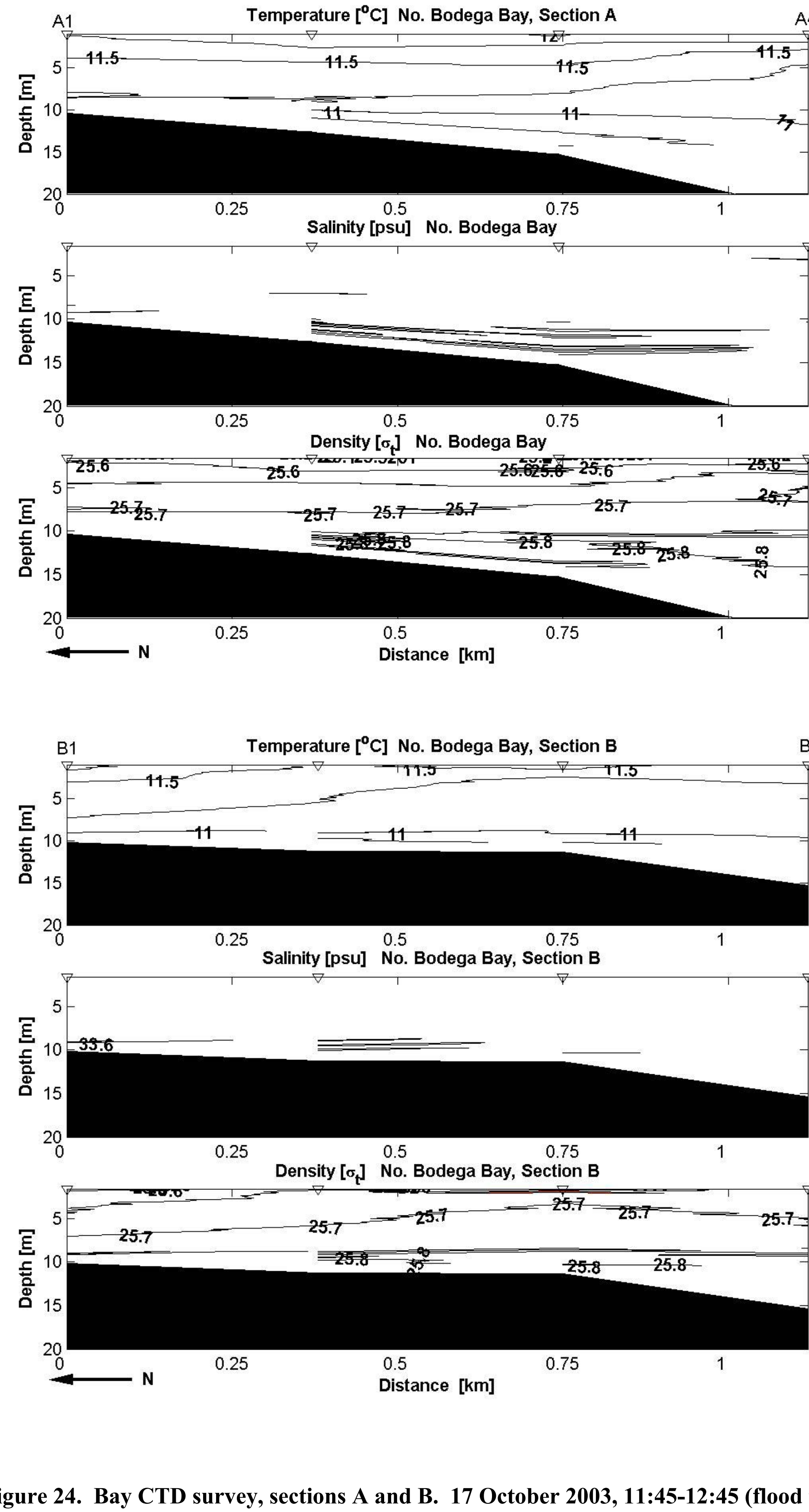


Figure 24. Bay CTD survey, sections A and B. 17 October 2003, 11:45-12:45 (flood tide).

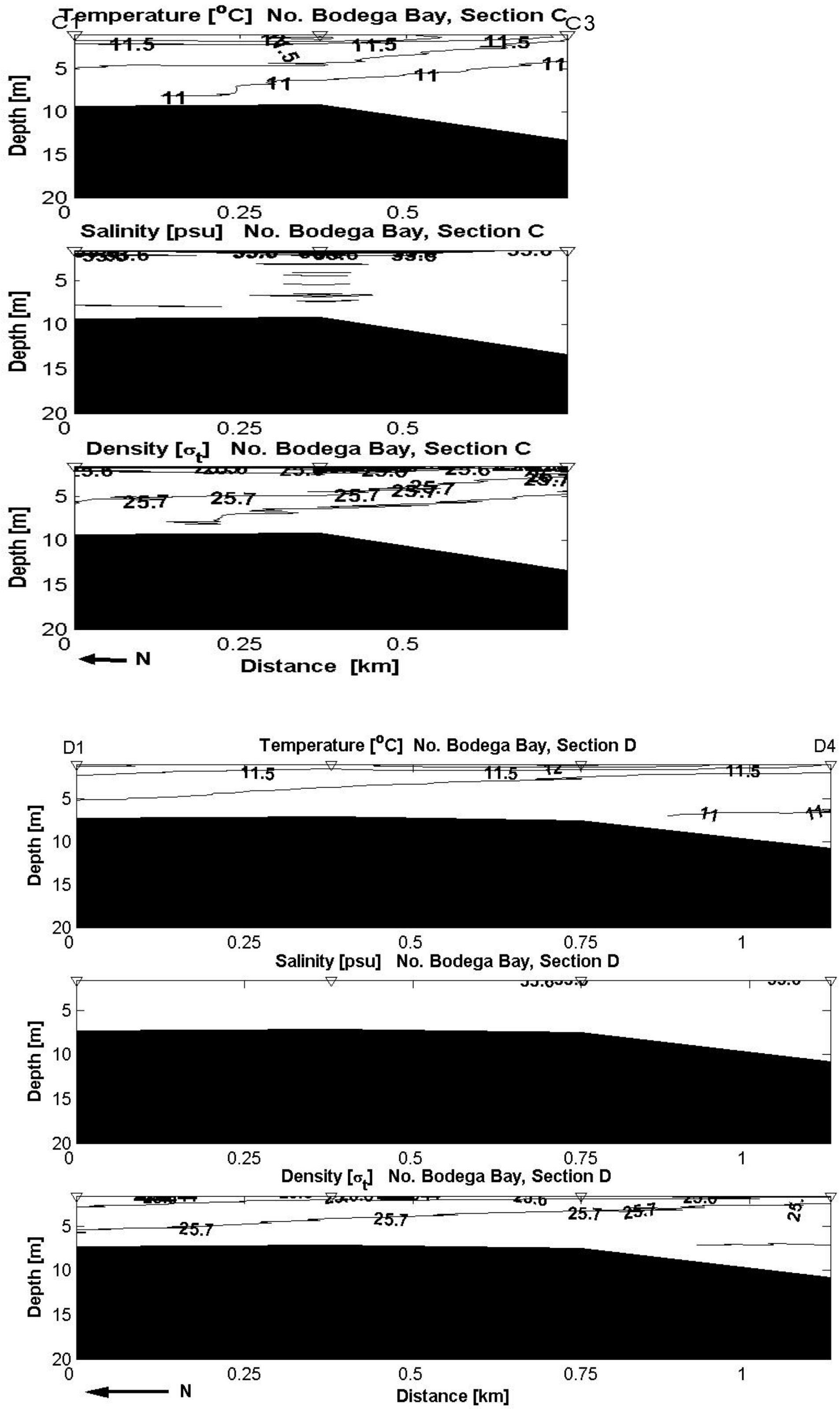


Figure 25. Bay CTD survey, sections C and D. 17 October 2003, 12:50-13:40 (flood tide). (Note: missing data at station C4, end of section C.)

C. Drifter Releases

Surface drifter experiments were conducted during the spring and fall studies, both inside and outside the harbor. The "Davis" style drifters used are approximately 3 feet deep with four 3x1 foot sails. Sets of drifters were released in the harbor during the fluorescein dye experiments (Section D) in the same location as dye patches to provide independent measures of current speed and direction.

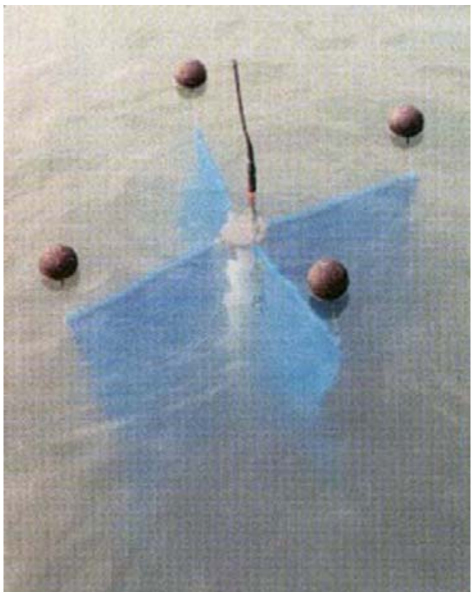


Figure 26. Shallow water "Davis Drifter". (Image from NOAA)

Harbor Drifters

Drifters deployed with the dye patches closely matched the movements of the dye and demonstrate the extent of the tidal excursion in Bodega Harbor. Figure 27 shows the drifter trajectories during the May 23rd dye experiment during a moderate ebb tide (tidal range during experiment was 1.7 feet). All channel drifters followed the outgoing tide as expected. The drifter velocities increased from an average of 14 cm/s to 33 cm/s as proximity to the channel mouth increased. This is consistent with the data from the ADCP units at the rear and front of the harbor. Unexpectedly, the two drifters placed near the marinas at Spud Point remained almost stationary. This indicates that unlike water elsewhere in the harbor, the marina does not always flush rapidly and thoroughly with each tidal cycle. Any contaminants from the marina may therefore have a negligible impact on Campbell Cove on a daily basis. However, if the flushing is consistently slow in the marina area, it is possible contaminants may accumulate such that when flushing does occur they are in high concentrations.

The drifters released with the Fall dye experiment also followed the dye patches closely, with speeds increasing closer to the harbor mouth (Figure 28). The tidal range during this experiment was approximately double that of the spring experiment (3.0 feet, ebb tide). Drifters released near the Spud Point marinas on this occasion did not remain stationary but moved slowly SSE across the tidal flats. This suggests it is only during weak tides that water in this area is isolated from the rest of the harbor.

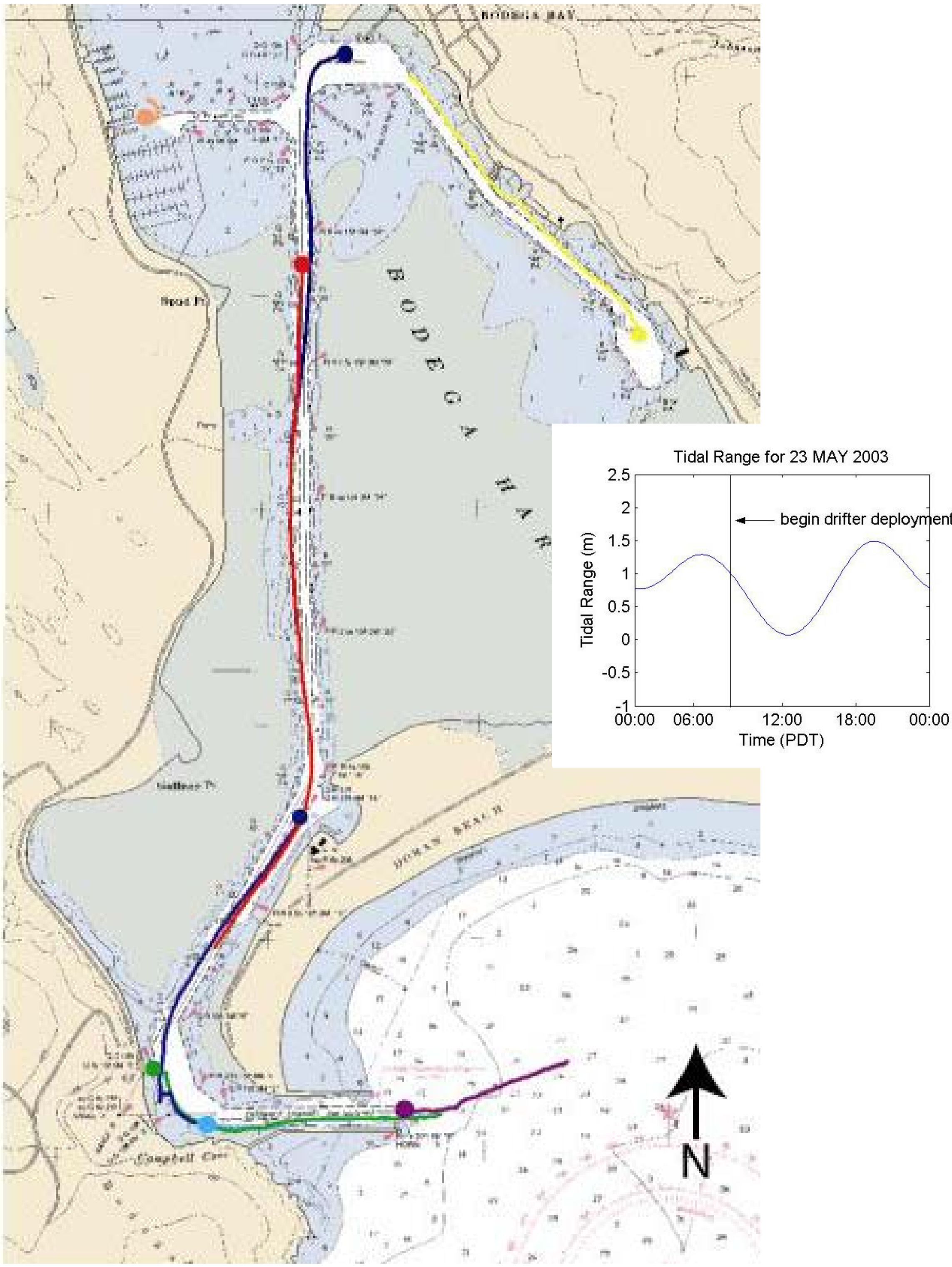


Figure 27. Drifter deployment, 23 May 2003. Tidal range 3.9 ft, range during deployment 1.7 feet (ebb tide). Circles indicate drifter starting positions.

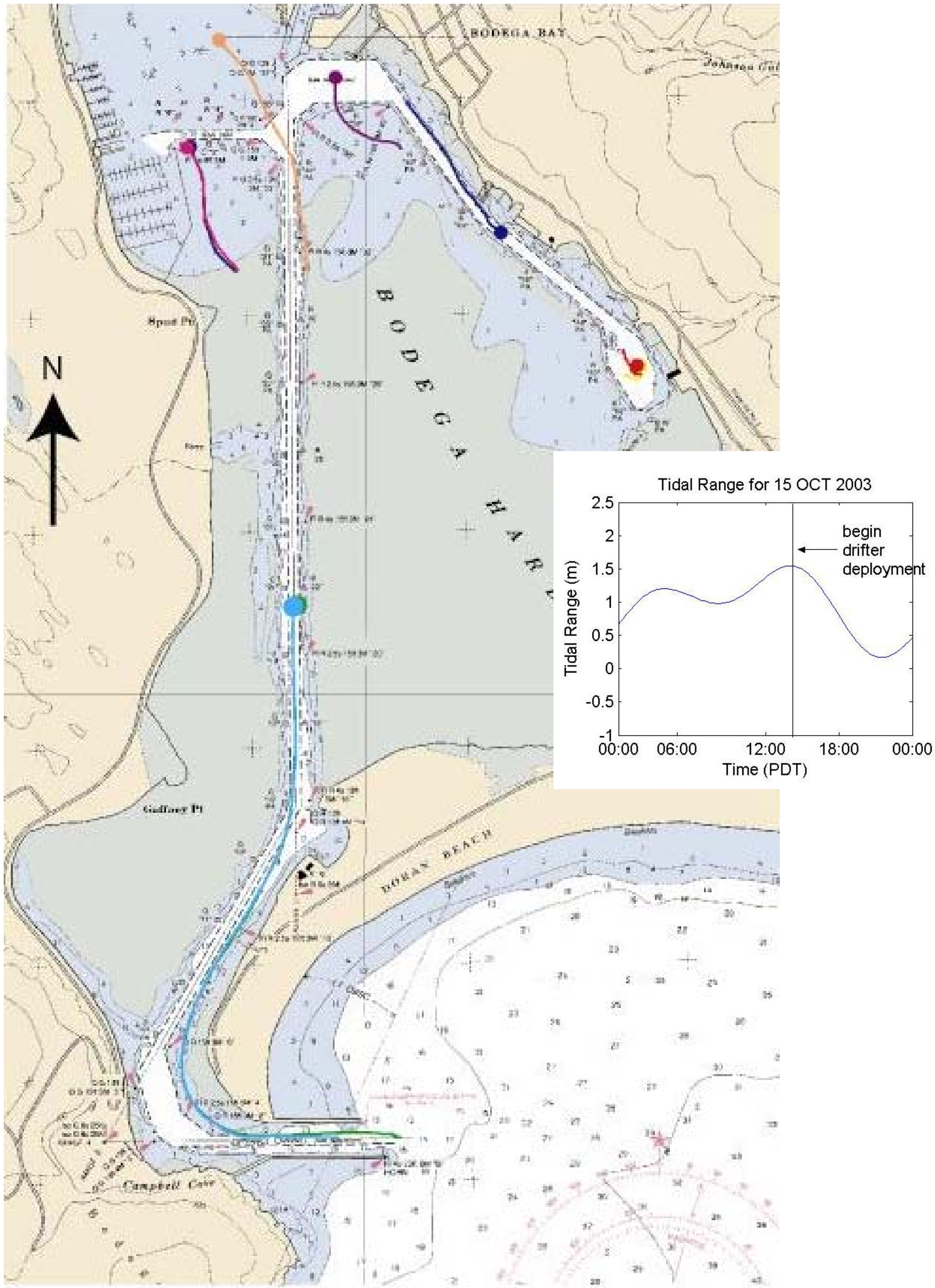


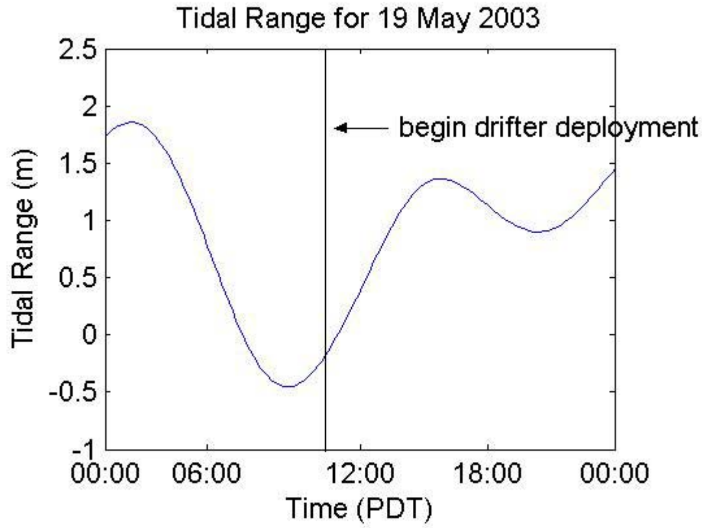
Figure 28. Drifter release, 15 October 2003, 14:00-16:00. Tidal range = 4.5 feet, tidal range during deployment ~ 3 feet (ebb tide).

Bay Drifters

To test the extent from which outer bay water influences the harbor, drifters were also deployed in an array in the bay near the mouth of the harbor at flood tides during both the Spring and Fall studies. In the spring experiment during a moderately strong flood tide, a small number of these drifters -- those nearest the harbor entrance-- actually entered the channel and progressed up into the harbor (Figure 29). The range over which surface water from the bay was entrained into the harbor mouth was small, extending not over 300 meters. Other drifters in the array followed a northeastward course up to the axis of the harbor channel (e.g., red and pink tracks), at which point they turned southeast.

During the Fall experiment, a slightly smaller array was deployed during a weak flood tide (Figure 30) and again only those nearest the mouth actually entered the channel, and only from the east of the mouth. All other drifters in the array moved rapidly southwestward toward Bodega Rock.

In both drifter experiments outside the harbor, the area of direct entrainment of surface water was quite small. It is possible that subsurface water may be entering the channel from a greater distance. However, if the water entering the channel is uniform in velocity from top to bottom at the mouth as it is at Campbell Cove, one could expect that bottom water is not entering the harbor at a greater rate than surface water. Water column temperatures in Campbell Cove also reflect the structure of temperatures outside the harbor, so it appears that water is entering the harbor in more or less equal amounts from the surface and bottom. It therefore appears unlikely that contamination originating more than a few hundred meters from the harbor mouth would be a significant source of contamination within the harbor at Campbell Cove.



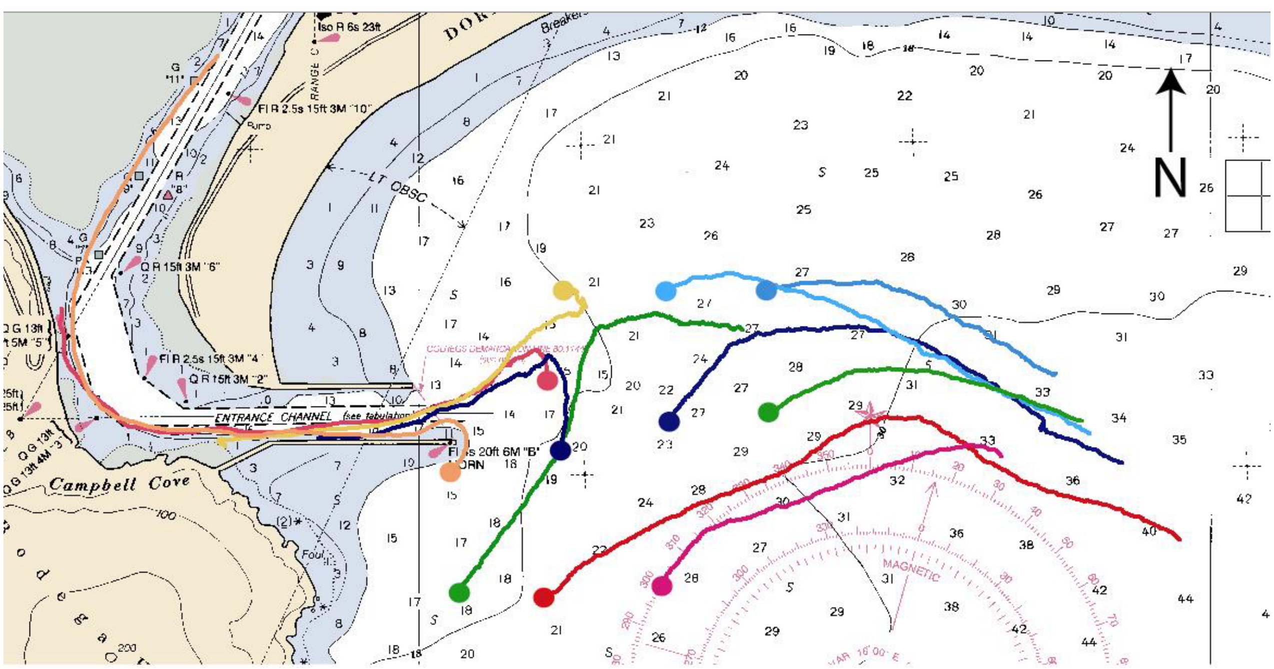
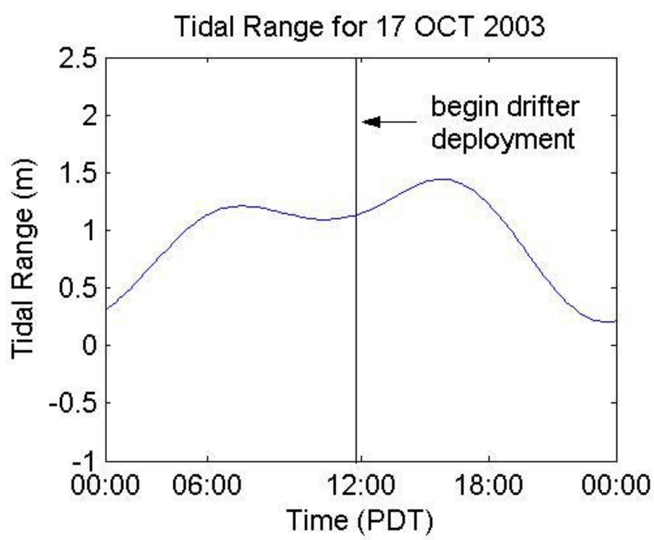


Figure 29. Drifter deployment, Spring 2003 (19 May). Circles indicate initial positions.



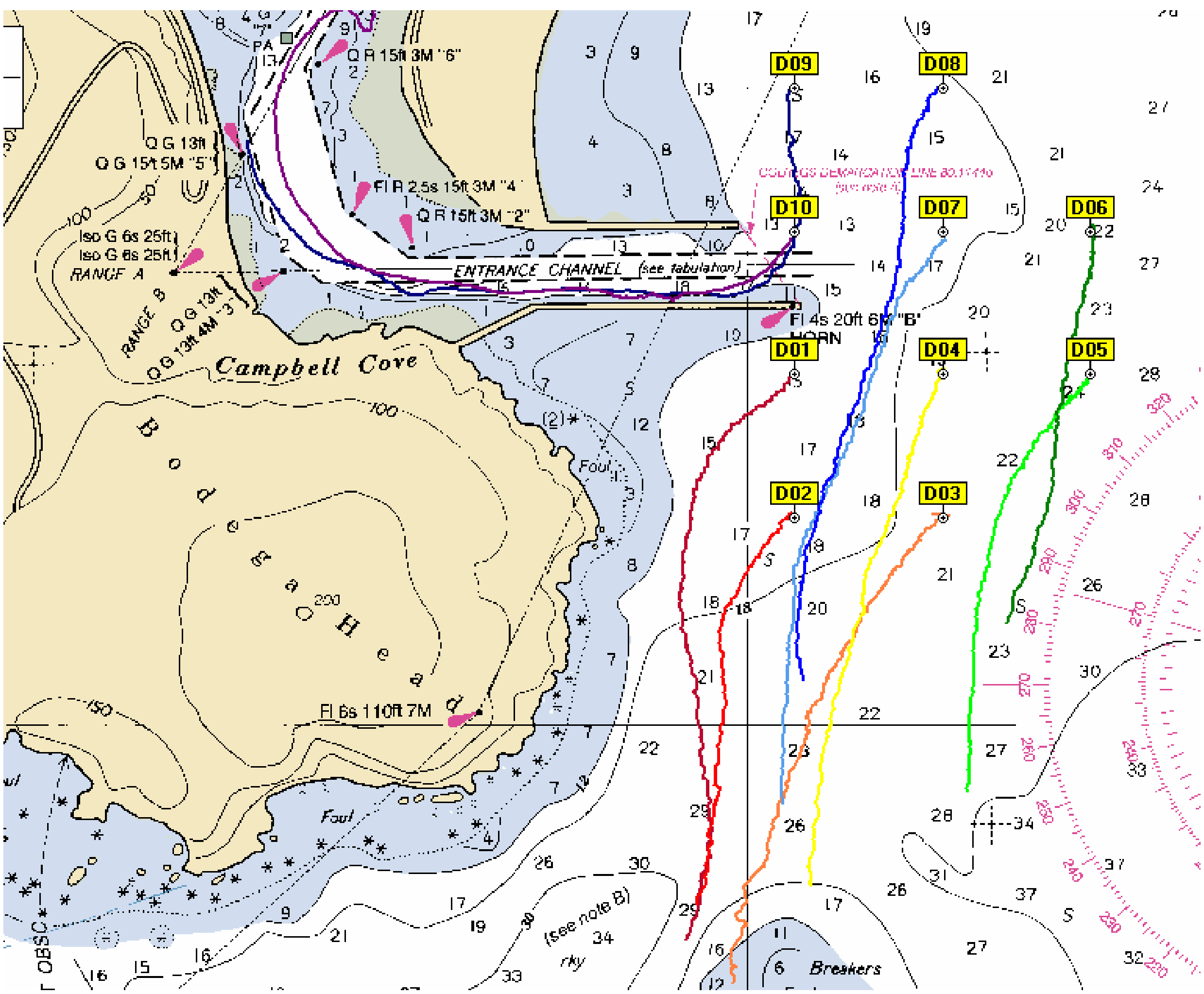


Figure 30. Drifter deployment, Fall 2003 (17 October). Yellow labels indicate initial positions.

D. Dye Releases

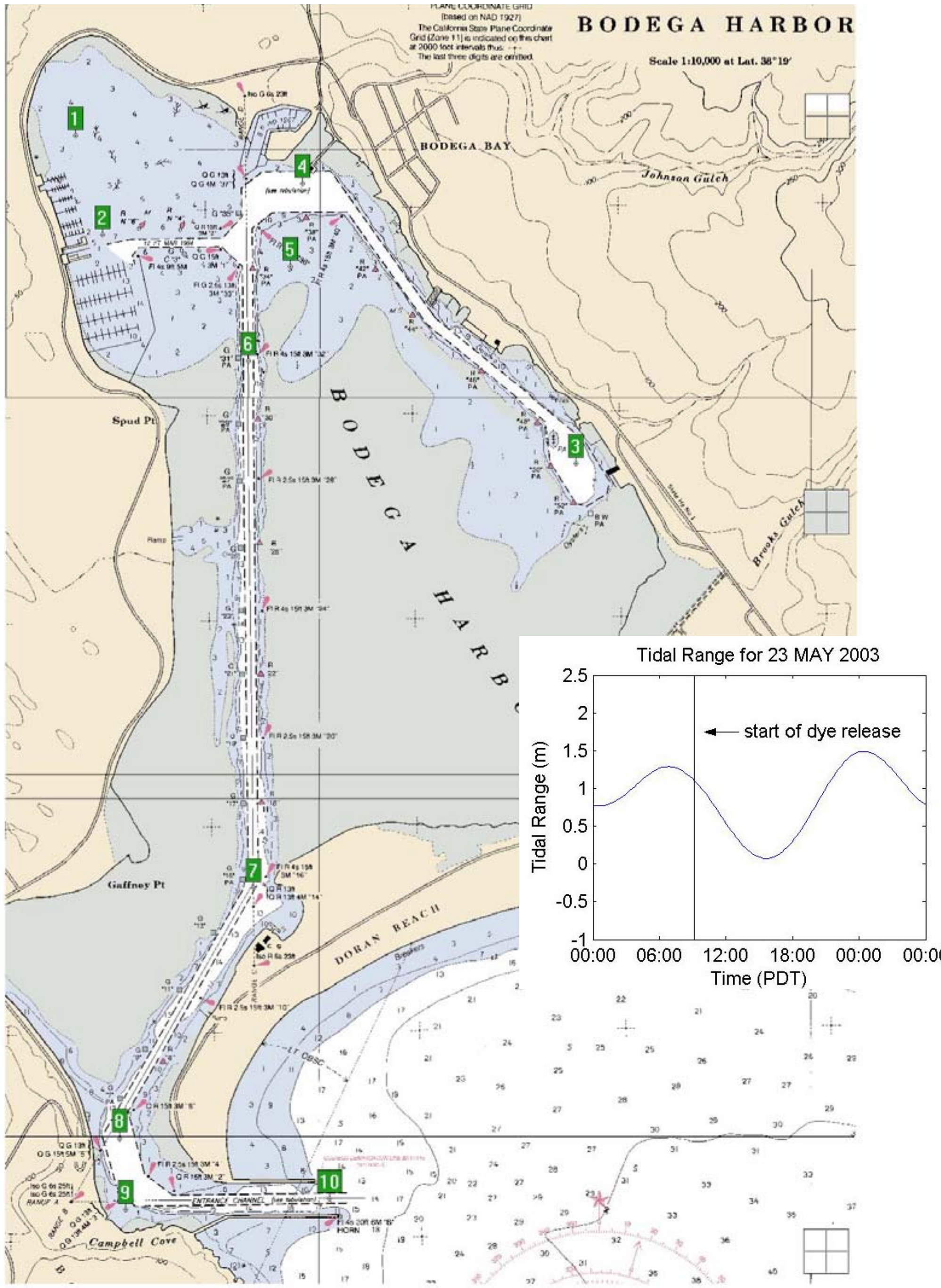


Figure 31. Fluorescein dye release locations, Spring 2003.

Dye tracer experiments were conducted with both rhodamine and fluorescein dyes to observe advection and dispersion of contaminants in the harbor. In the fluorescein experiments, dye was released in discrete patches throughout the harbor during ebb tides. Where water depth allowed, drifters were also released concurrently to track surface currents. The progression of the bright green fluorescein dye patches was recorded using digital aerial photography. Figure 31 and Figure 32 show the initial locations of the fluorescein dye patches during the Spring and Fall experiments respectively. Yellow markers on the Spring map indicate dye releases over the tidal flats which were not accompanied by drifters. Additional patches not shown on the map were released over the tidal flats near Gaffney Point. The tidal range during the Fall ebb tide was slightly greater than that during the Spring (3.0 ft during Fall experiment vs. 1.7 feet during Spring).

The patch behaviour shown in the images is consistent with other results from ADCP, CTD and drifter observations, and also gives additional insight into dispersive behaviour of contaminants and the effects of the tidal flats, shallow beaches and vegetation.

Digital Aerial Images

The digital photographs of the dye patches were processed using an orthorectification algorithm developed by Dr. Linden Clarke of Scripps Institution of Oceanography to normalize for elevation and the deviation of the angle of the plane and camera from horizontal. The rectification scheme uses exact locations of 50 ground markers around the perimeter of Bodega Harbor surveyed in by Dr. Clarke in May 2003. The pixels corresponding to the markers are then identified in the digital images for use in the rectification program.

The photographs shown are rectified such that patch size and location can be directly compared between images. In all rectified images, the north-south axis is exactly vertical (north upward). Some images were not able to be rectified due to lack of sufficient ground markers in some photographs, or because of the large scale of overview photographs; north is indicated graphically on these images.

For reference, the chart in Figure 33 shows the approximate location of the aerial images in the following sections.

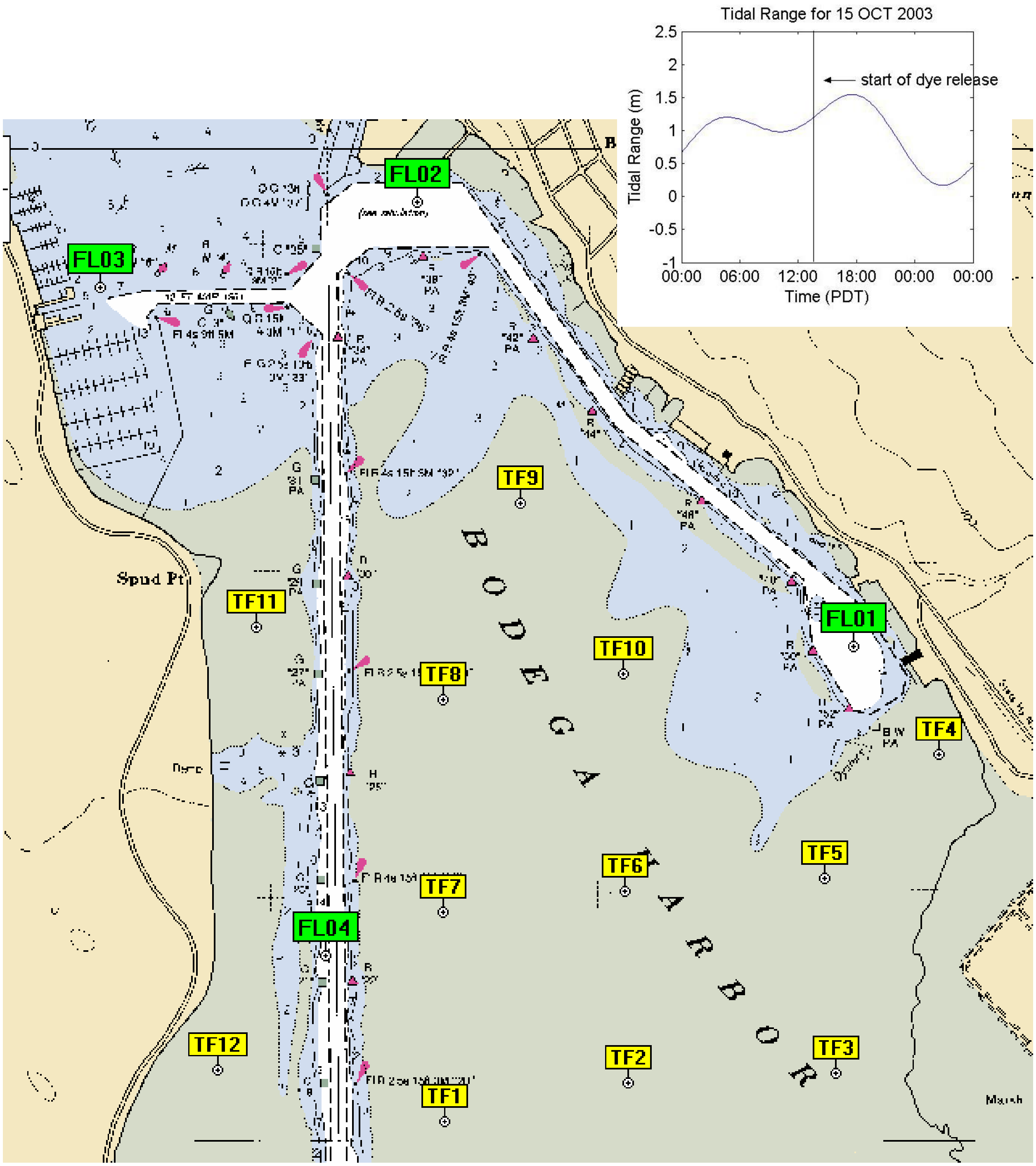


Figure 32. Fall 2003 Fluorescein dye release, 15 October 2003. Green markers indicate dye and drifter releases in the main channel areas. Yellow markers indicate dye releases over the tidal flats.

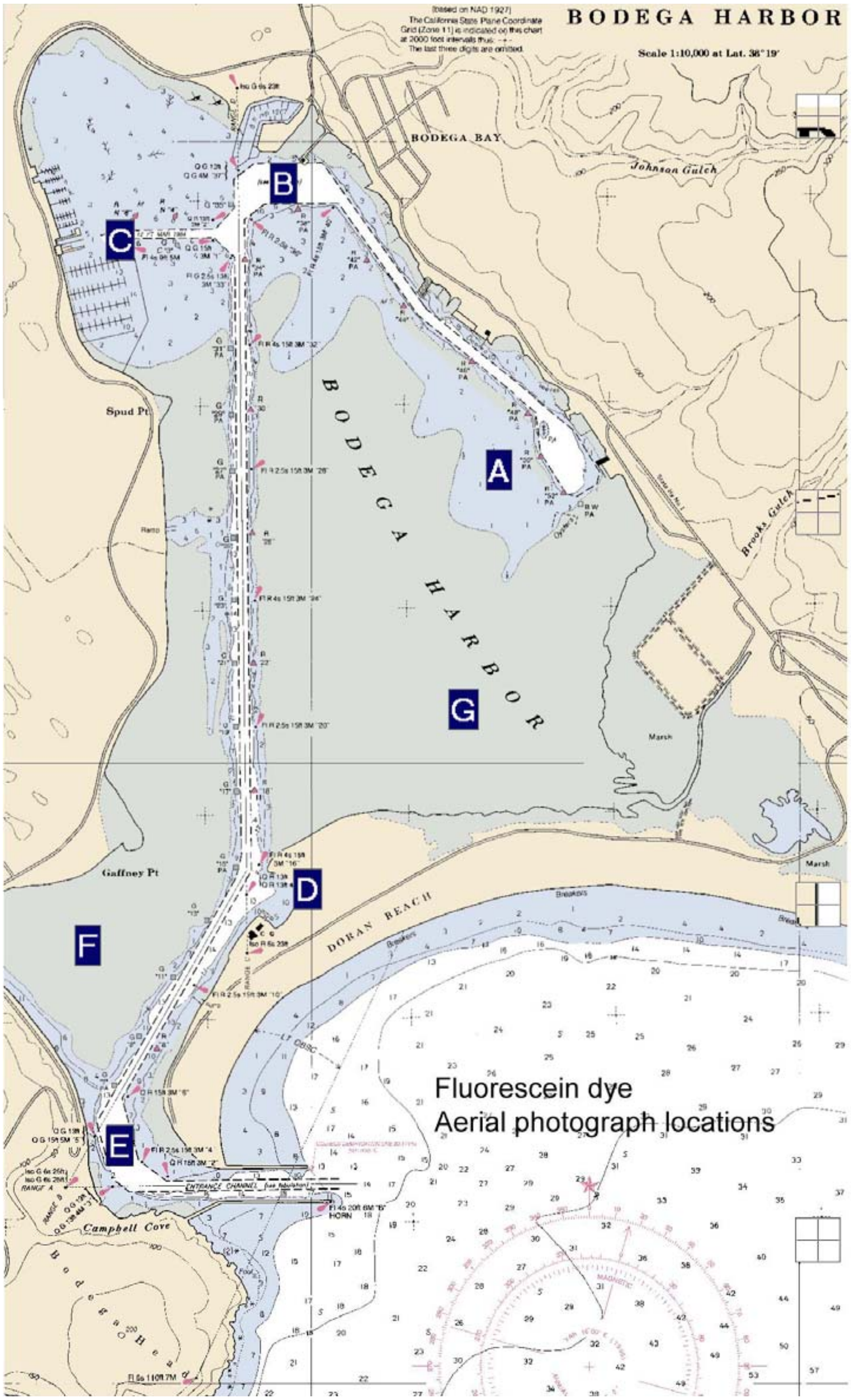


Figure 33. Sites of aerial photographs of fluorescein dye patches.

Figure 34. Fluorescein dye, Spring 2003, Bodega Harbor channel end (east). Elapsed time: 38 min. Image location A (see Figure 29).

Back Harbor, channel and marinas

Dye patches from the rear of the marina generally moved less rapidly and dispersed more than those in the main channel or near the mouth of the harbor. Figure 34 shows the movement and dispersion of dye from the end of the channel during the fall dye release. After about an hour of slow movement down the channel, this patch was no longer detectable due to dilution. The same patch position in fall remained trapped at the channel end (Figure 35).

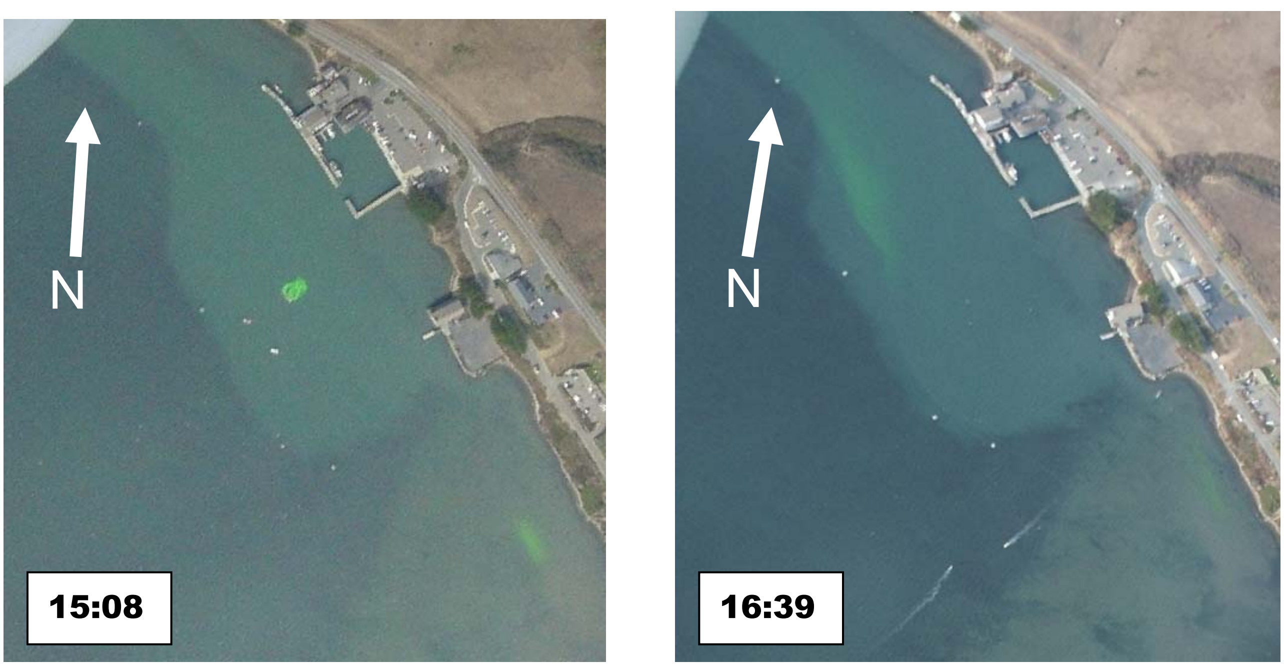


Figure 35. Fluorescein dye experiment, Fall 2003, Bodega Harbor channel end (east). Elapsed time: 91 min. Image location A (see Figure 29).

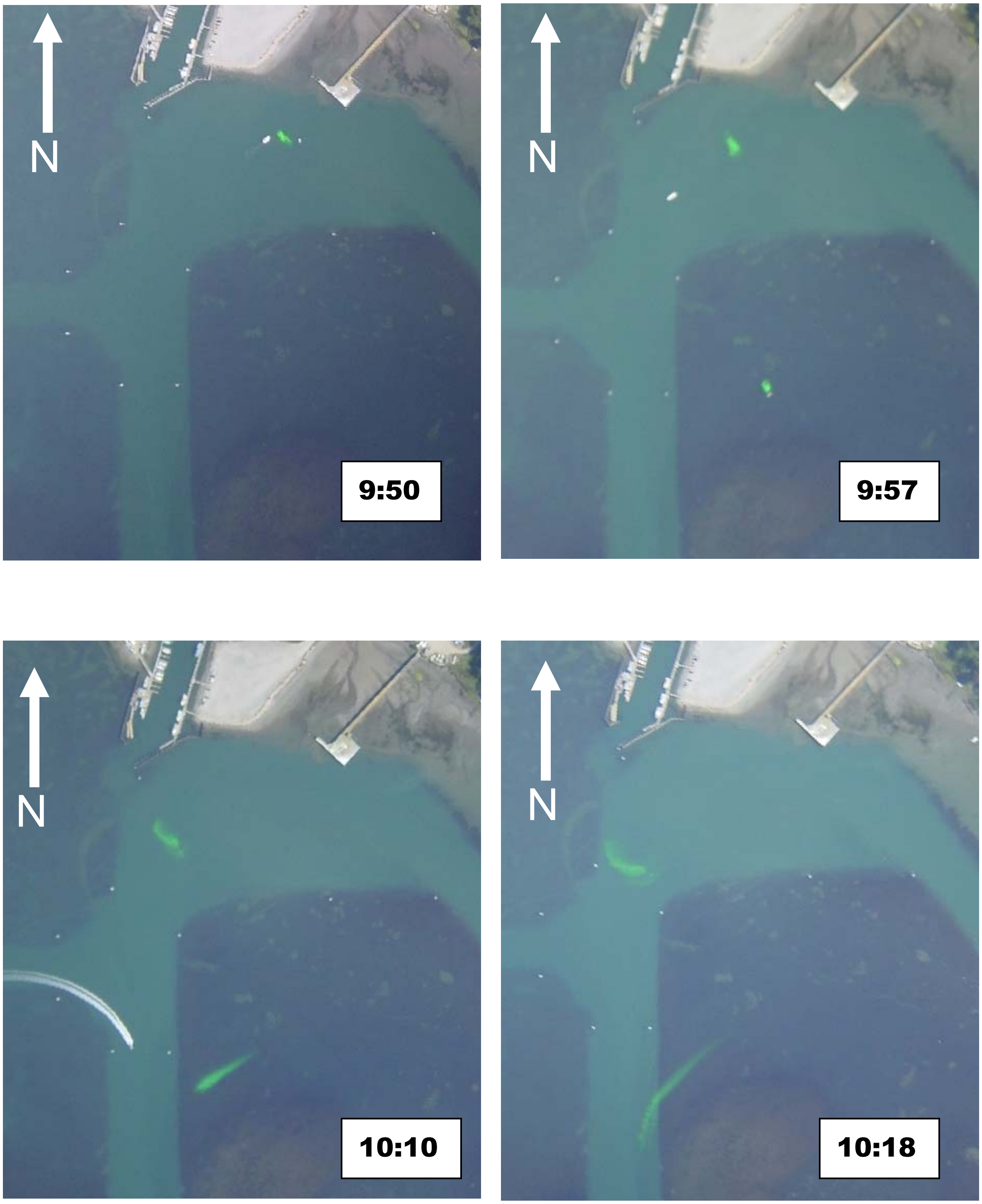


Figure 36. Fluorescein dye experiment, Spring 2003, Bodega Harbor north. Elapsed time: 21 min. Image location B (see Figure 29).

Patches released at the north (rear) of the harbor near Porto Bodega moved through the channel slowly, around 10 cm/s (Figure 36 and Figure 37) and were completely diluted within an hour.

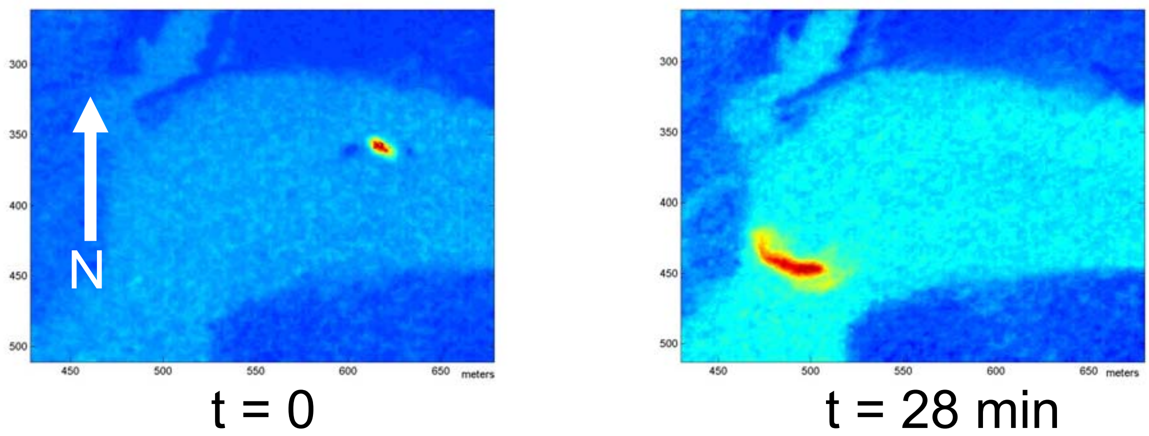


Figure 37. Dye patch advection, rear channel, Spring 2003. Advection rate 9.5 cm/s. Image location B.

A patch released in the same location in the Fall experiment moved even more slowly, persisting in the back harbor for over an hour after drifting over the tidal flats (Figure 38).

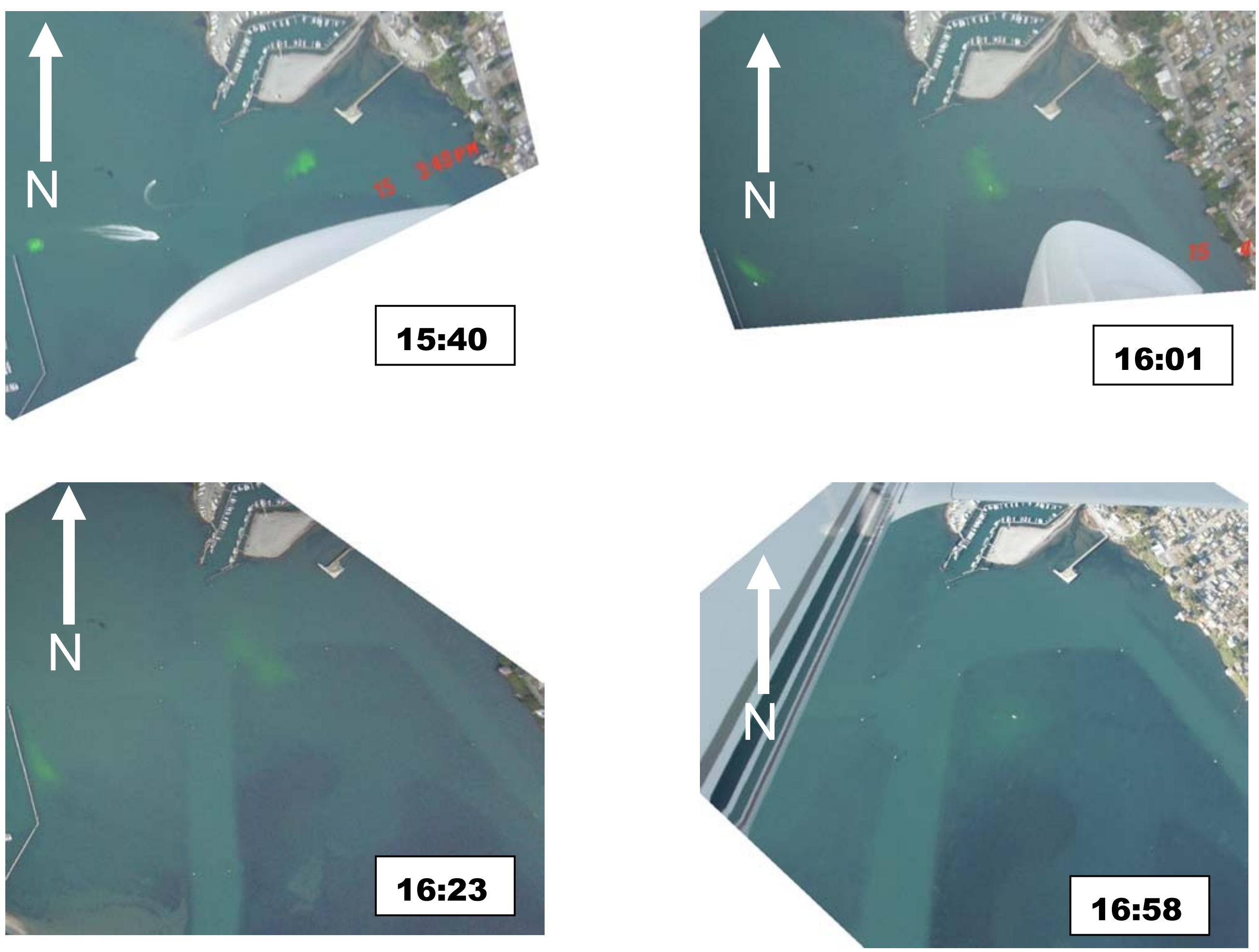


Figure 38. Fluorescein dye experiment, Fall 2003, Bodega Harbor north. Elapsed time: 78 min. Image location B.

The slowest advection occurred near the Spud Point marinas in Spring (Figure 39), where the patches remained nearly stationary throughout the experiment, while showing significant dispersion. (Calculations of the dispersion rate for this patch is shown at the end of this section, Figure 51 and Figure 52).

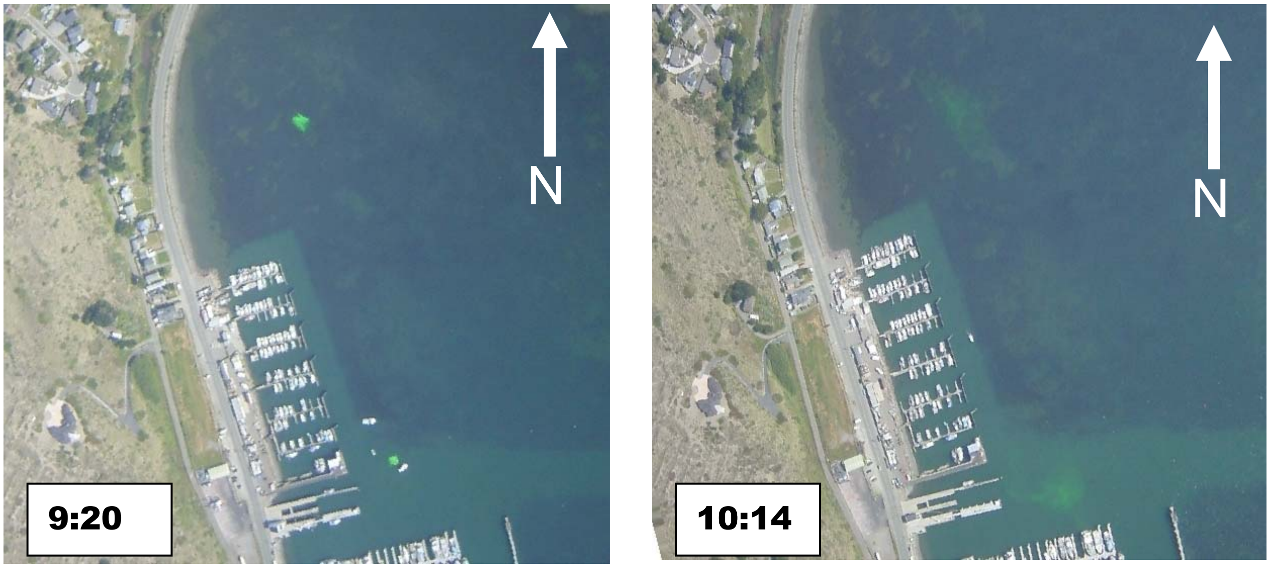


Figure 39. Fluorescein dye experiment, Spring 2003, Spud Point Marina. Elapsed time: 54 min. Image location C.

A dye patch released just outside the marinas in Fall also remained in the area for a long time, but did move slightly over the tidal flats (Figure 40).

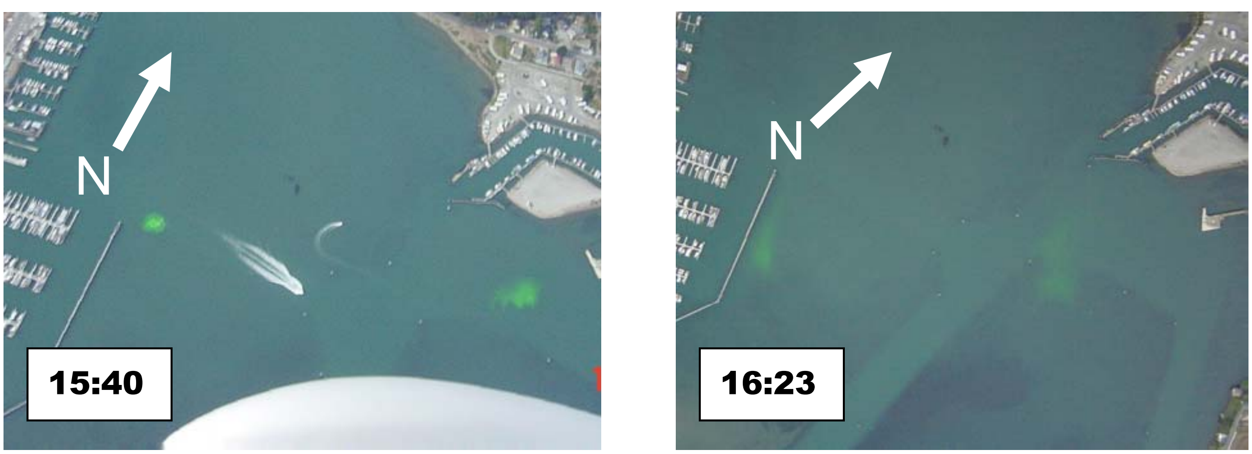


Figure 40. Fluorescein dye experiment, Fall 2003, Spud Point Marina. Elapsed time: 43 min. Image location C.

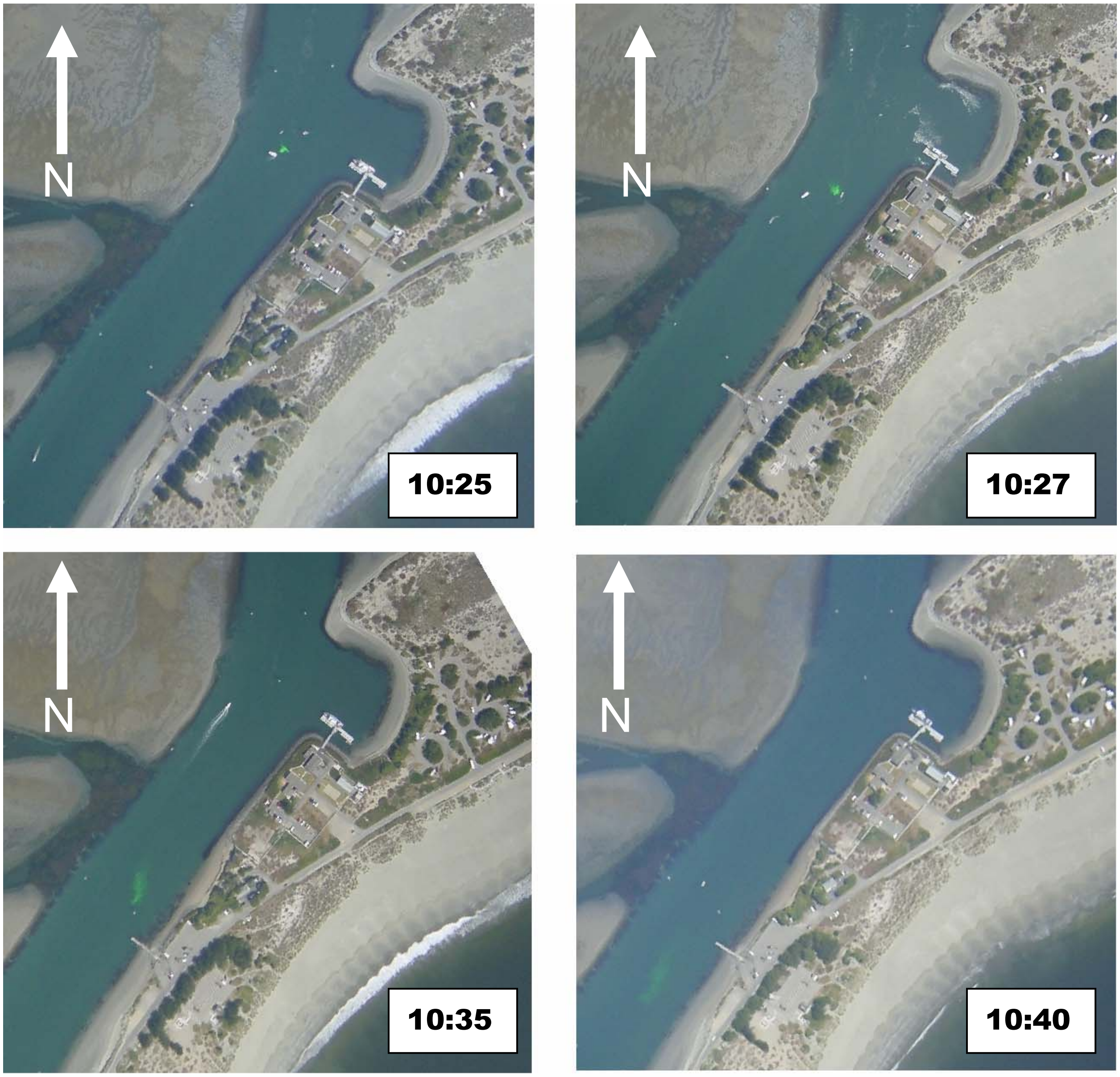


Figure 41. Fluorescein dye experiment, Spring 2003, harbor lower channel at Coast Guard Station. Elapsed time: 15 min. Image location D.

Central Channel

Advection of dye patches in the central channel between Spud Point and Campbell Cove was rapid, consistent with velocities observed in surface drifters as they approach the mouth and ADCP velocities at Campbell Cove. The patch shown above (Figure 41) has a velocity of 33 cm/s during a moderate ebb tide.

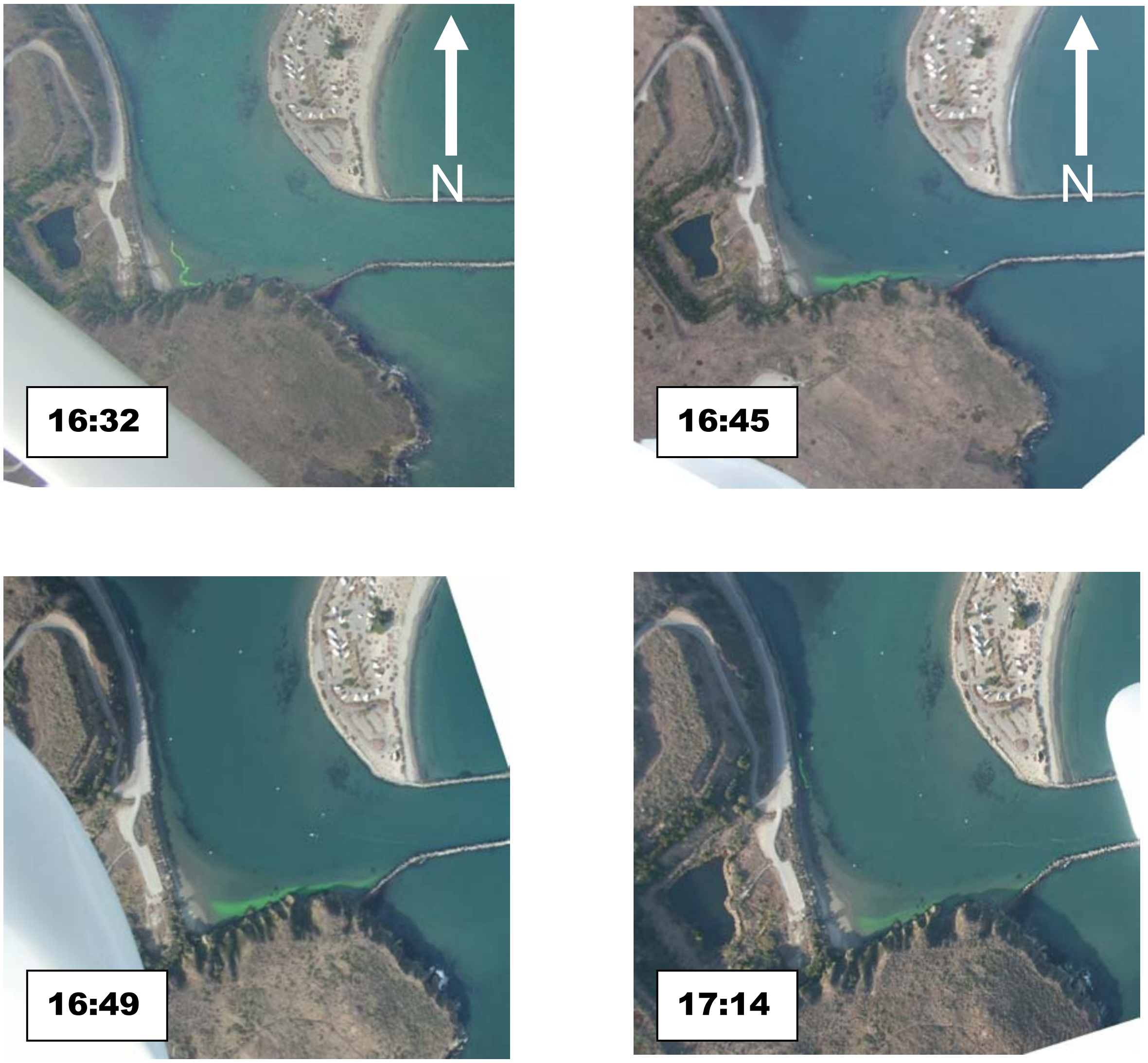


Figure 42. Fluorescein dye experiment, Fall 2003, Campbell Cove. Elapsed time: 42 min. Image location E.

Campbell Cove

Dye released at or near Campbell Cove displayed a tendency to become trapped at the edges. In the rhodamine dye experiment (see next section) this was observed visually in a large dye patch which was advected up the channel during a flood tide, but left some residual dye along the northwest side of the cove in an area with eel grass. The patch shown above from the Fall experiment was positioned to determine the fate of a contaminant released directly into water at the Campbell Cove beach. As with the rhodamine dye, it persisted at the edge of the cove while dispersing along a thin line into the main channel entrance. No evidence of this patch was visible the following morning. However it is possible that a local contamination source at Campbell Cove could remain concentrated at the shoreline if it was being released continuously or at closely spaced intervals in time. This may be especially true in waters shallower than we were able to sample by boat. In depths less than half a meter, contaminants could become trapped in the boundary layer at the edge of shore and persist for longer periods of time.

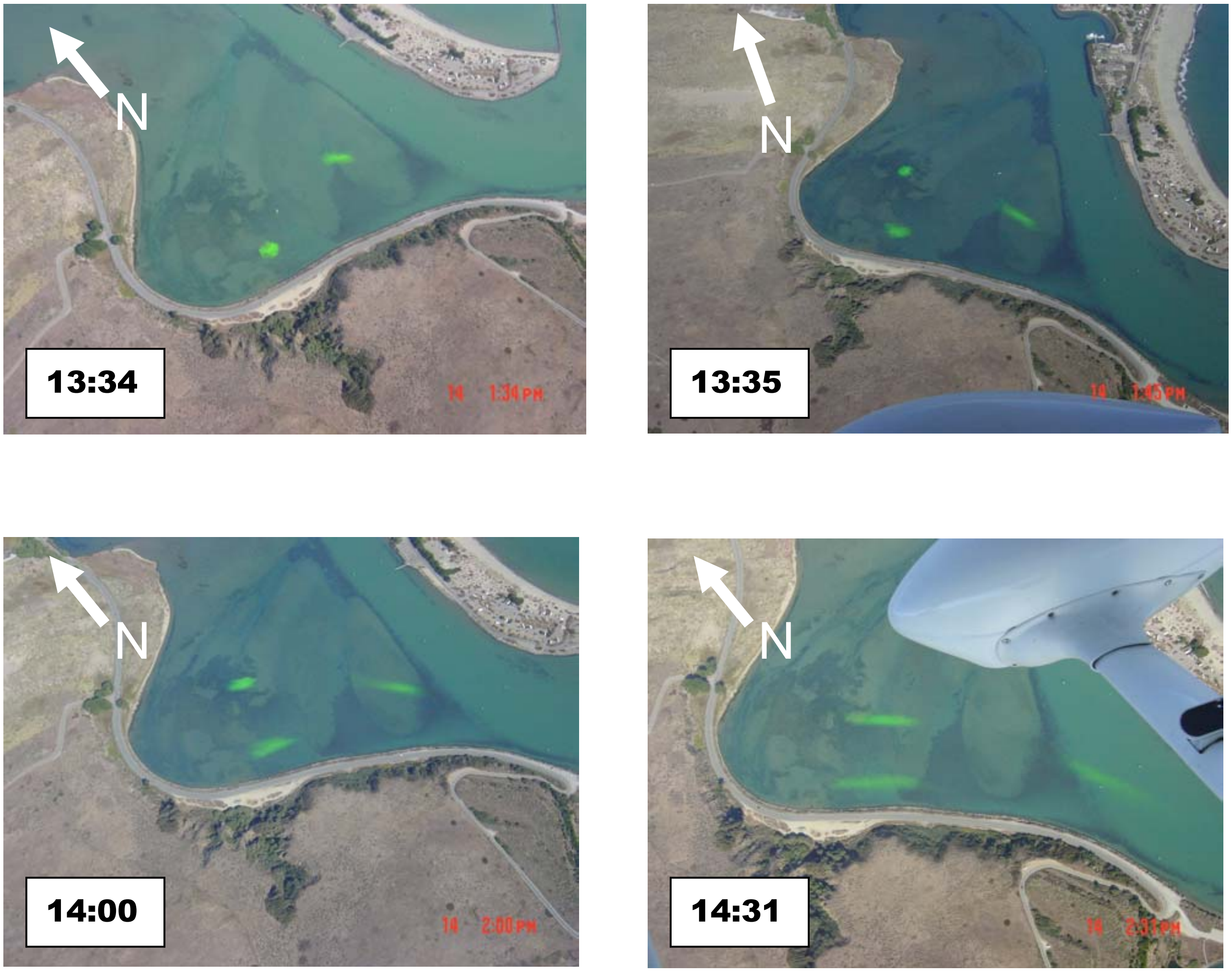


Figure 43. Fluorescein dye experiment, Fall 2003, Gaffney Point tidal flats. Elapsed time: 31 min. Image location F.

Tidal Flats

Due to concern over bird populations on the harbor tidal flats being a potential source of bacterial contamination at Campbell Cove, dye studies in the fall included fluorescein patches over the main tidal flats to the east of the channel and those near Gaffney Point to the west of the channel. Figure 43 shows dye patches released over the Gaffney Point tidal flats. The concern here was that drainage of the flats at ebb tide might direct tidal flats water to the edge of the flats along the south and into Campbell Cove. The main flow off the tidal flats is directly toward the channel where the patch is quickly dispersed (see image at 14:31). While flowing toward the main channel, the patch nearest the southern edge of the flats did drift shoreward somewhat (Figure 44). However, an hour later (approximately 3 hrs 15 minutes since initial release) all of these three patches have been incorporated into the main channel flow. In the last image of the series (Figure 46) there is no visible trace of the three patches released over the Gaffney Point flats, and no residual dye can be seen at the Campbell Cove beach area. Dye patches introduced at the Campbell Cove beach after the Gaffney Point patches have also been advected out of the area.

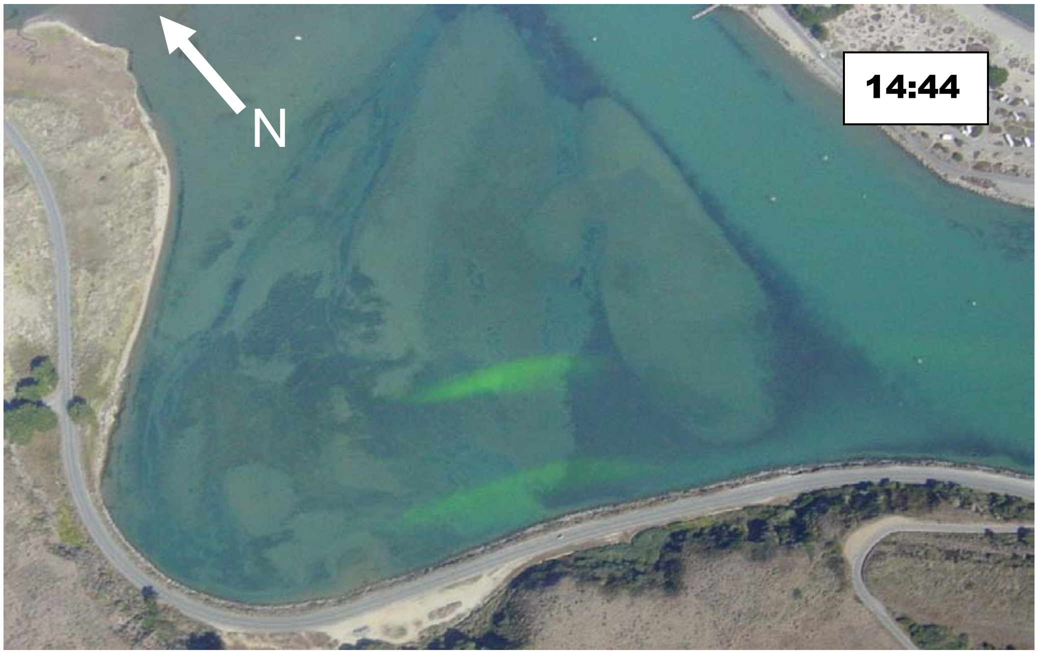


Figure 44. Gaffney Point fluorescein dye experiment. Note drift of southernmost patch (bottom of image) toward shore as it moves toward main channel (at right). Image location F.

Figure 45. Gaffney Point fluorescein dye experiment, approximately 3.5 hours after initial dye release. Image location F.

The following day a similar experiment was conducted over the main tidal flats west of the channel. (See patch locations, Figure 32.) With the exception of patches released near the end of the channel (rear patches 3, 4, 5) the dye moved off the flats toward the southwest, toward and into the central channel. The rear patches showed little advection, and dispersed in place through the experiment. Patches 9 and 10 at the north of the channel moved slowly southward and toward the central channel, while flow off the flats was most rapid from the southwest portion (patches 1,2,6,7,8). In this region drainage was sometimes directed into small channels within the flats such as that shown in Figure 47; patches 6 and 7 flow into a small channel which empties into the main harbor channel.

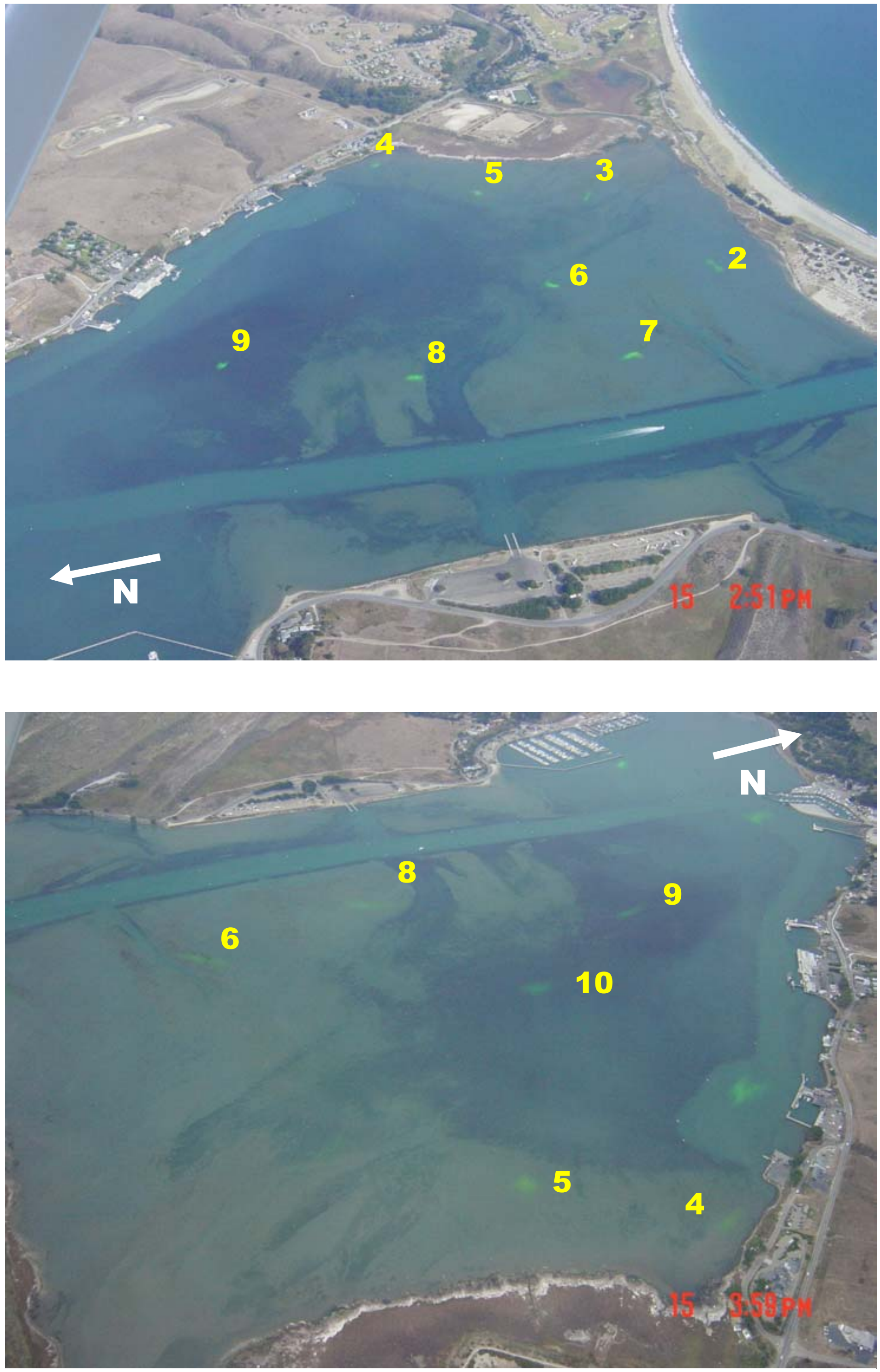
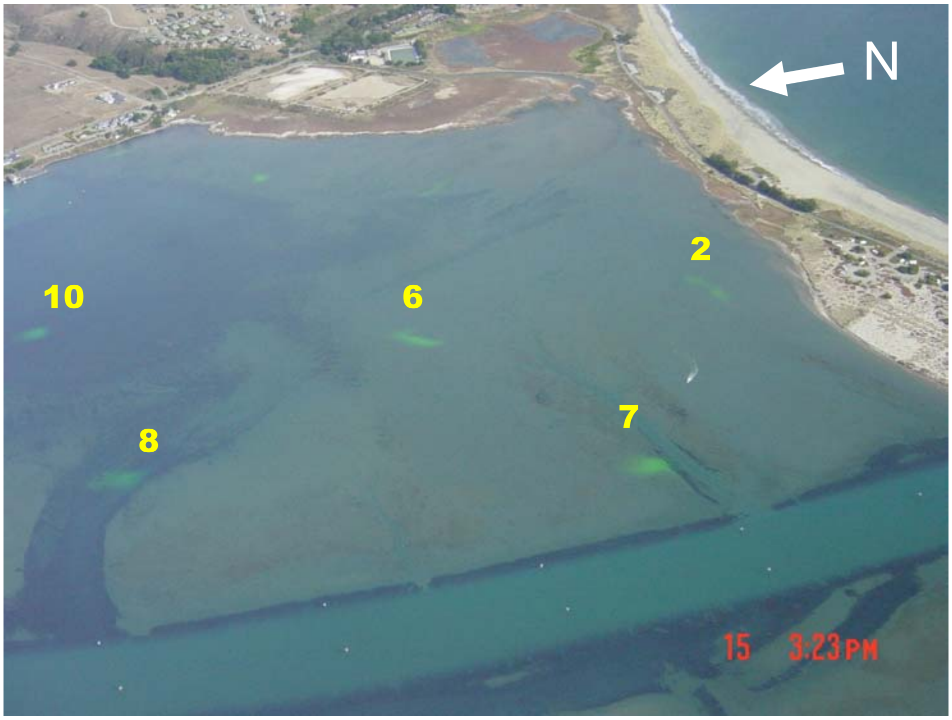


Figure 46. Tidal flats, fluorescein dye experiment, 15 October 2003. Image location G.



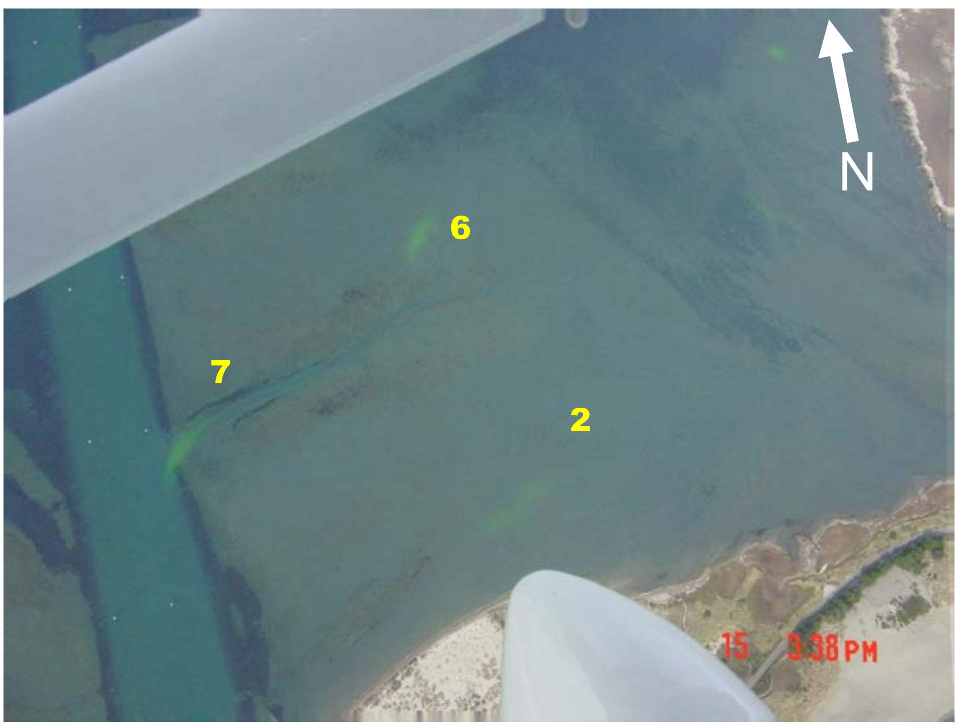


Figure 47. Flow of dye patches (#6 and #7) into small channels on the tidal flats. 15 October 2003. Image location G.

Dye dispersion experiments, Campbell Cove and Rear Harbor

Figure 48. Deployment of rhodamine dye in Campbell Cove, May 2003.

Rhodamine dye experiments were conducted by saturating basins with the red dye in order to determine its persistence in the basin, potential avenues of transport, and dispersion rates. The dye concentrations were measured using boat-mounted fluorometers for continuous underway data, as well as separate casts for vertical profiles through the dye patches.

In the spring experiment, a large dye patch was introduced into Campbell Cove at flood tide to investigate its persistence in the cove and harbor over a tidal cycle. The dye moved rapidly out of the cove and into the main channel, where it dispersed somewhat as it traveled up into the harbor. Upon arrival at the back of the harbor (near Porto Bodega) the patch rapidly dispersed to both the east and west of the central channel and was undetectable by the end of the flood tide. Figure 49 shows the concentration of dye through the center of the patch as it travels from Campbell Cove to the rear of the harbor.

A similar experiment was conducted in Fall 2003 to test dispersion from the rear of the harbor. In this dye release, a large patch of rhodamine was introduced near Porto Bodega at the north end of the harbor at ebb tide. The patch did not move as rapidly into the channel as the Campbell Cove patch, but dispersed out from Porto Bodega through the tidal cycle. (This is similar to results from ADCP showing slower flow rates in the rear of the harbor, and fluorescein dye experiments in which patches at the rear of the harbor moved more slowly than those closer to the mouth.) Figure 50 shows the dispersion over time through the center of the dye patch. The vertical distribution of dye in the water column is shown below. Mixing occurred down to about 4 meters depth, where a slight thermocline was present.

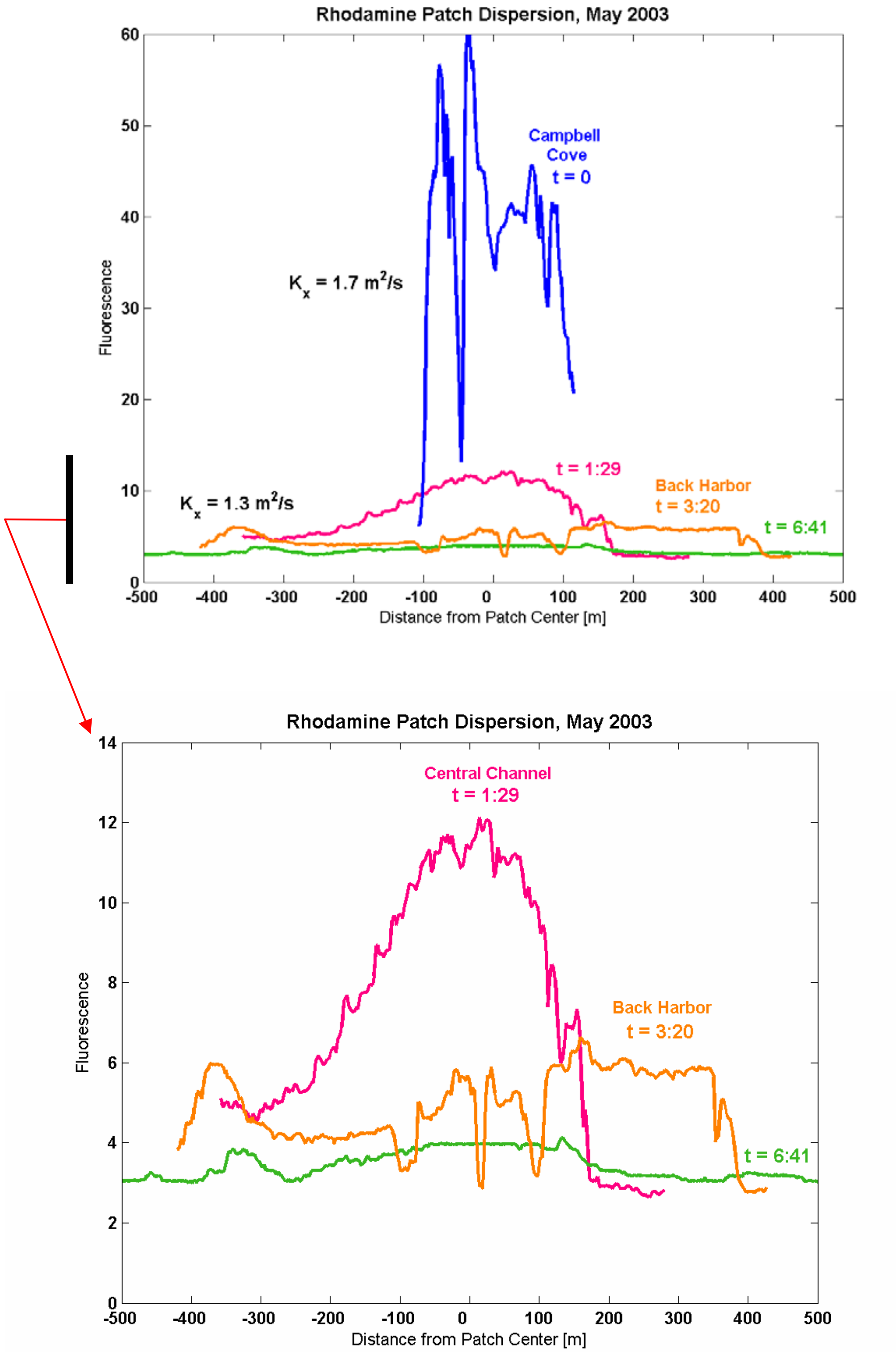
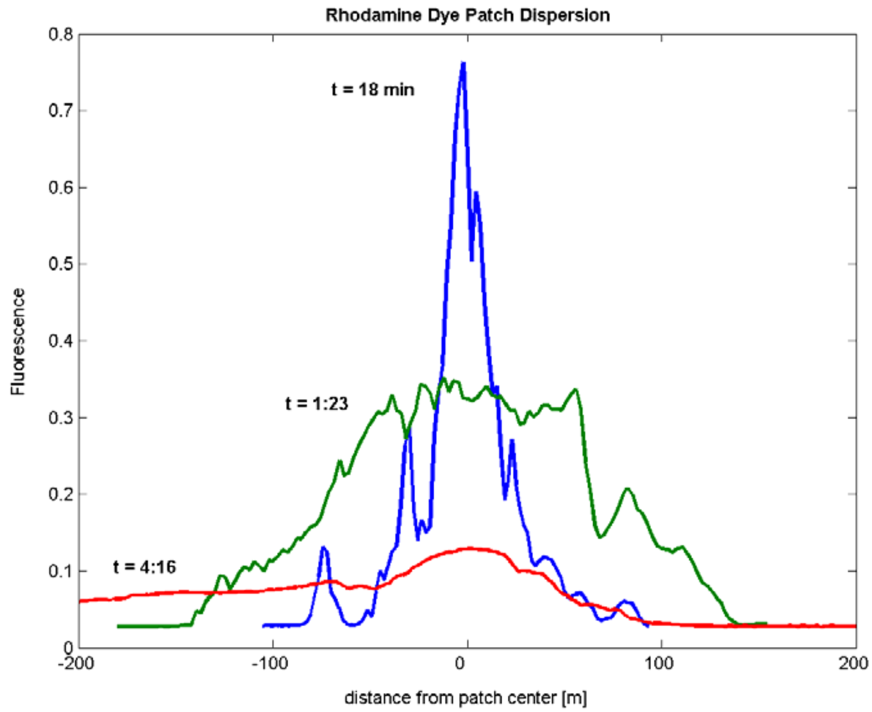


Figure 49. Dispersion of rhodamine dye in Bodega Harbor, Spring 2003, Campbell Cove through central channel to rear harbor. Bottom figure is a magnification of the three later curves.



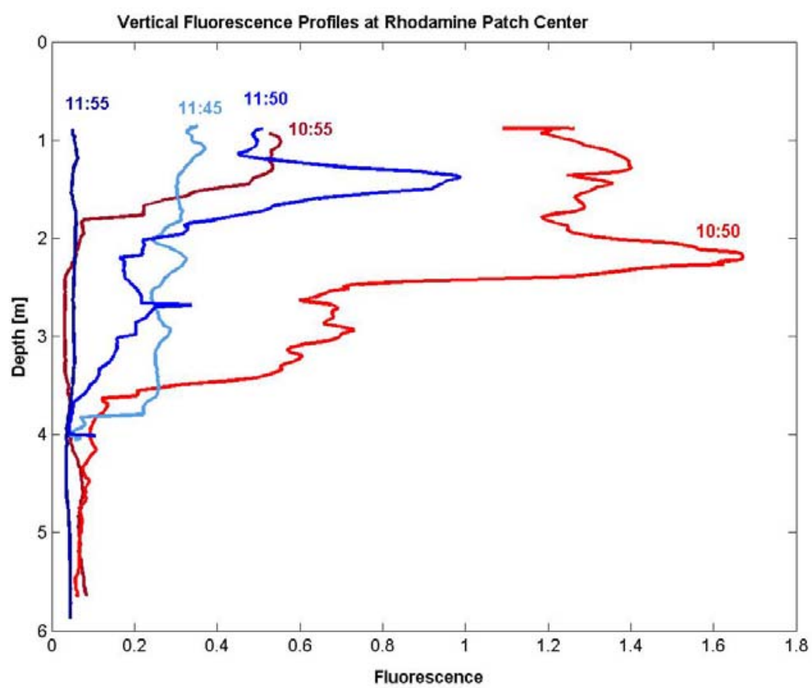
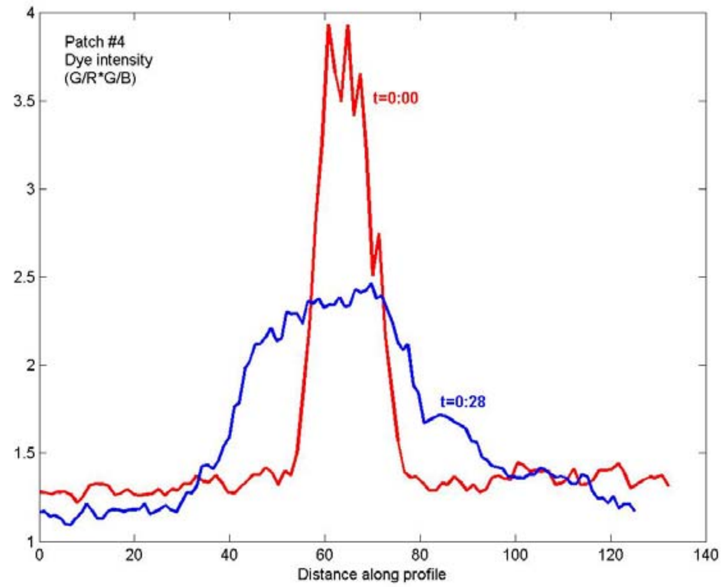


Figure 50. Dispersion of rhodamine dye in Bodega Harbor, Fall 2003, rear channel (Porto Bodega). Top: horizontal dispersion, Bottom: vertical dispersion.

Longitudinal dispersion



Cross-patch dispersion

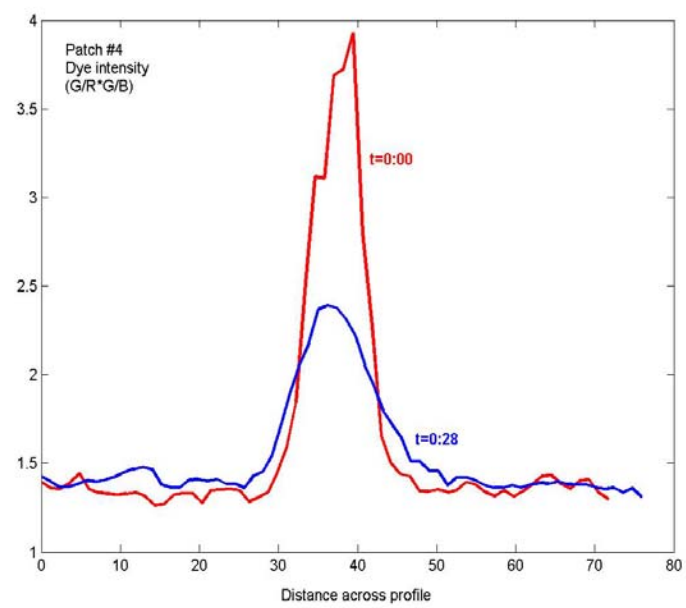


Figure 51. Dye patch dispersion, Spring 2003, rear channel.

Dispersion of the fluorescein dye patch in the rear harbor near Spud Point Marina from the Spring 2003 experiment is shown in Figure 51.

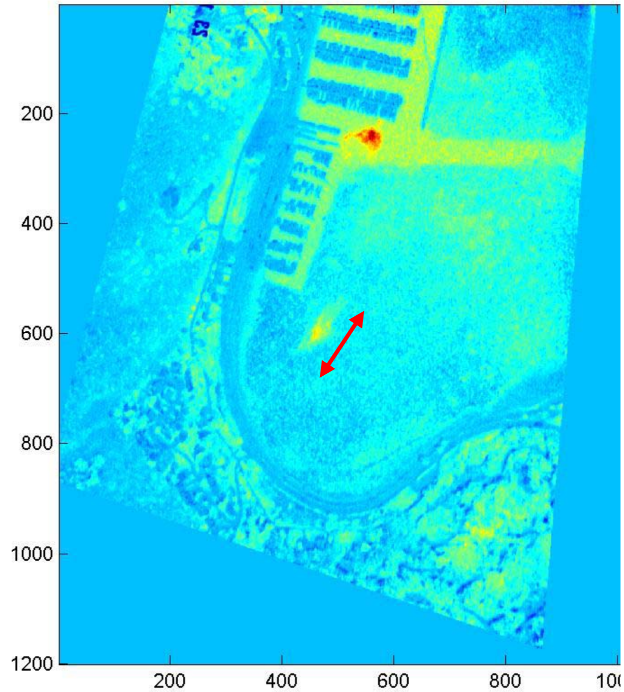
Dispersion rates calculated for the marina area from the spring fluorescein experiment are shown in Figure 52. Although advective velocities in the rear of the harbor are small, the dispersion rates are large enough to provide significant mixing of waters that can eventually enter the main channel where rapid advective exchange occurs. However, the water that enters the main channel has undergone a large amount of dilution by this time.

Dispersion rates measured near the marina are similar to other back bay areas (e.g., Mission Bay, San Diego). Although slower than more energetic mixing regimes, dispersion is the dominant transport mechanism in these areas due to the lack of advection. Within the channel advective transport dominates and makes measurements of dispersion logistically difficult.

Marina Dye Patches #1 & 2 after 1 hour

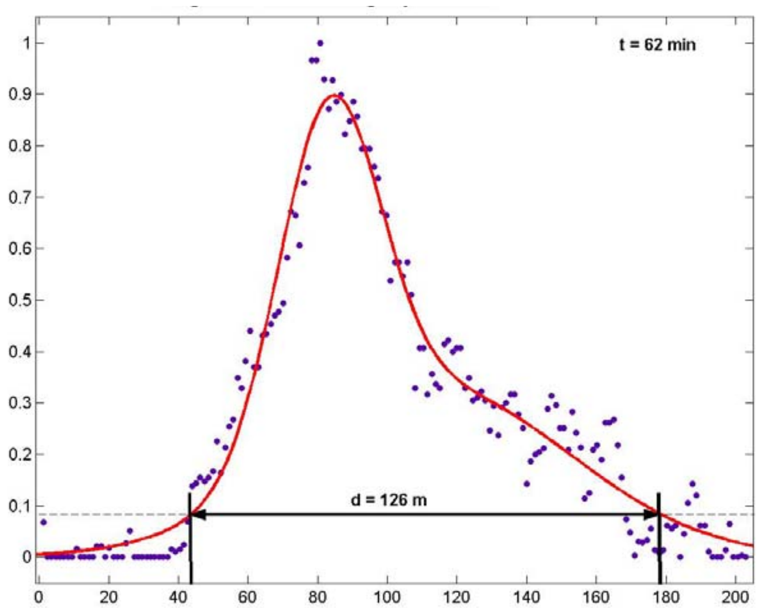
T = 62 min (10:14)

Enhanced Image



Color channel Ratio (G/R * G/B)

Dye Intensity through Longitudinal Patch Section



$K_x = 3\, d\sigma^2/dt$

$d = 4.3\ \sigma_x$

$d_{t=0} = 6m$ $d_{t=62} = 126m$

Horizontal Dispersion Rate:
$K_x = 1.06\ m^2/s$

Figure 52. Dispersion rate calculated from dye patch in Spud Point marina.

E. Temperature Sensors

A sample of the temperature data collected from moored thermistor strings is included here. Thermistor moorings were set up with surface, mid-depth, and bottom sensors in the main channel, and surface and bottom sensors in the shallower tidal flats. (In tidal flats, only the surface sensors proved to be useful as the other set became exposed to the air at low tide.) For a map of thermistor mooring locations, see Figure 53.

Features that can be seen in the temperature record include significant surface warming, especially in the rear of the harbor, and stratified temperatures at ebb tides when warmed surface water is exiting the harbor, but not during flood tides when colder bay water is entering. The temperatures at Campbell Cove fully reflect the bay water inputs at flood tide, and rear harbor waters at ebb tide which is expected from the ADCP data which shows unstratified flow (similar velocities from top to bottom) fully flushing the area.

Temperature figures included are for the Campbell Cove mooring, a mid-channel mooring, and a rear harbor mooring. Temperatures are in degrees Celcius. Each location has the complete series of either Spring or Fall temperatures on top, followed by zoom-ins of two individual weeks within that season. Each figure includes the data from surface, mid-depth and bottom sensors. Two additional figures show a comparison of the surface temperature record only for the three locations (Figure 60) and a comparison of the bottom temperature record for the three locations (Figure 61).

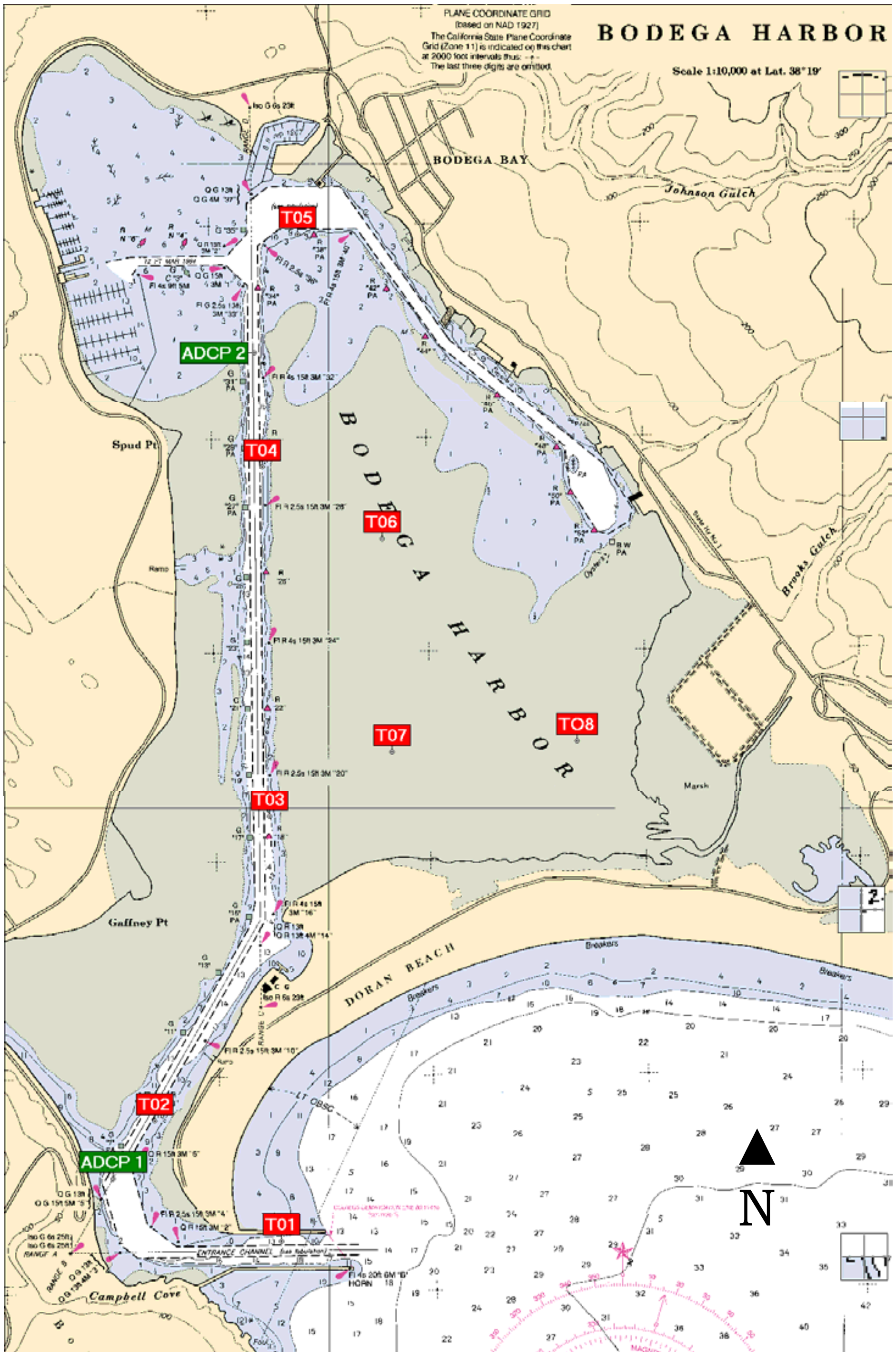


Figure 53. Thermistor mooring locations (red markers).

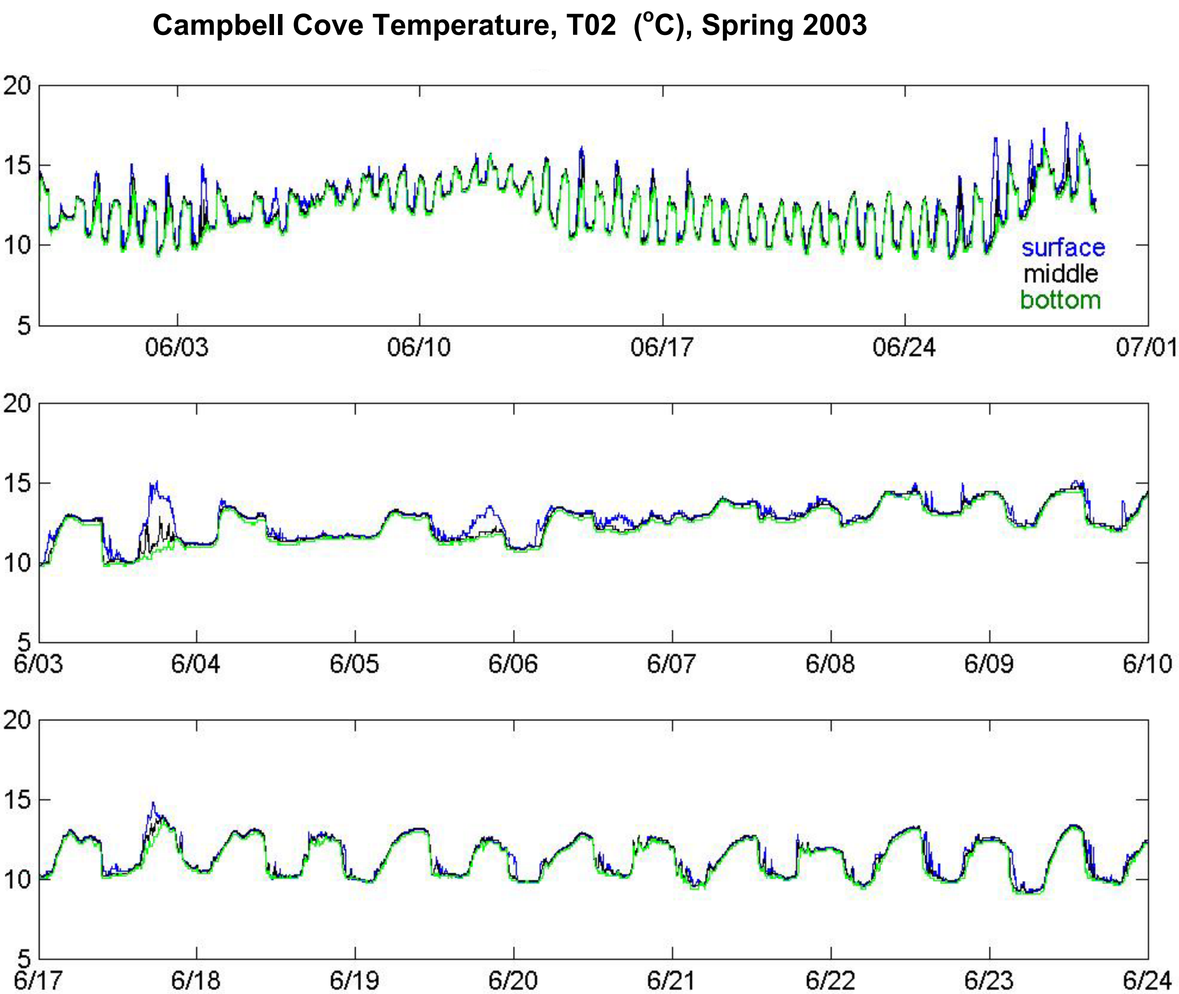


Figure 54. Temperature at Campbell Cove mooring, Spring 2003. Top: full record. Center: week of June 3-10. Bottom: week of June 17-24. Note uniformity between surface, mid-depth, and bottom temperatures during most of the record. Only during the largest warming events is significant stratification evident in the surface water (e.g., June 4 and 6).

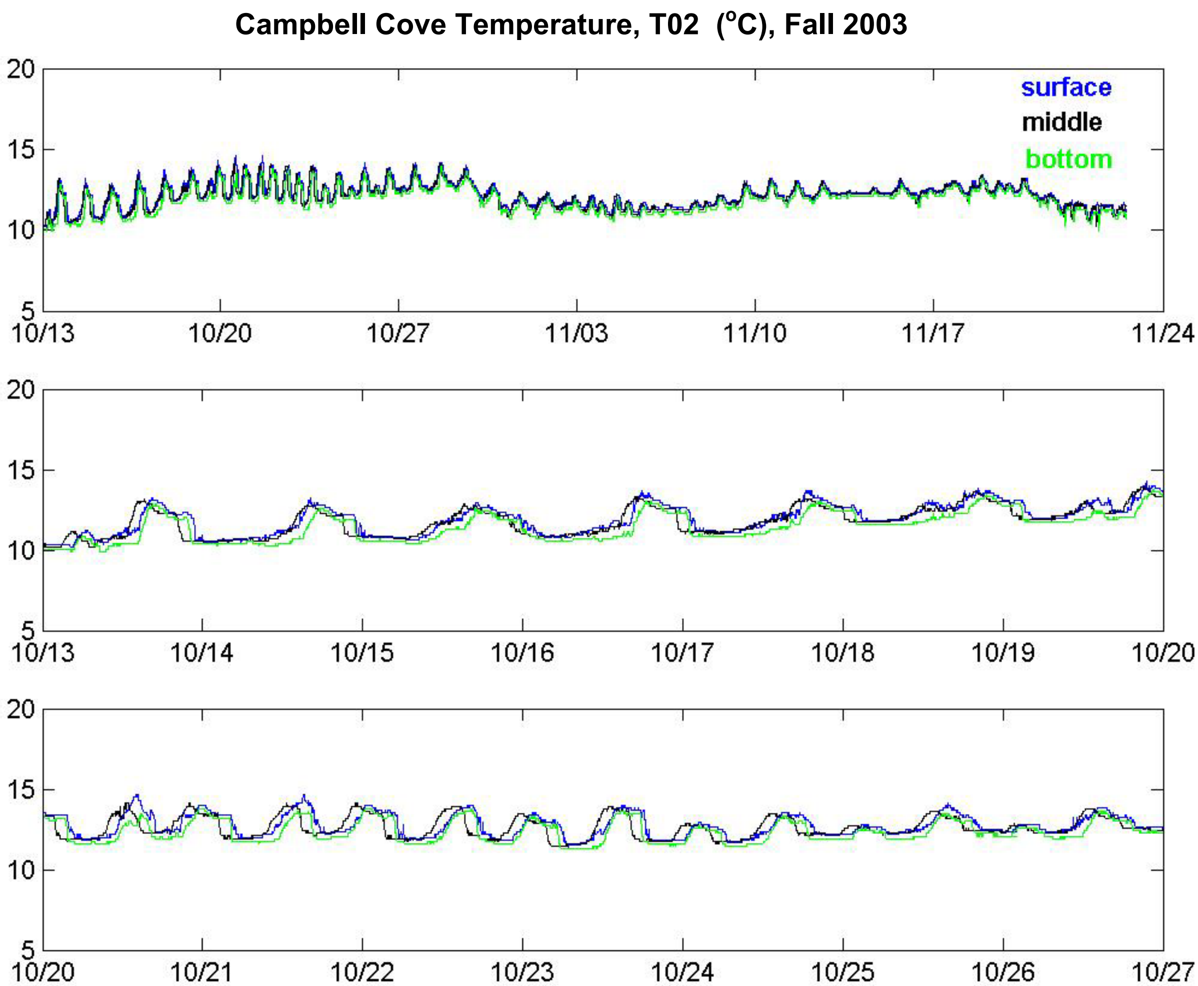


Figure 55. Temperature at Campbell Cove mooring, Fall 2003. Top: full record. Center: Week of October 13-20. Bottom: week of October 20-27.

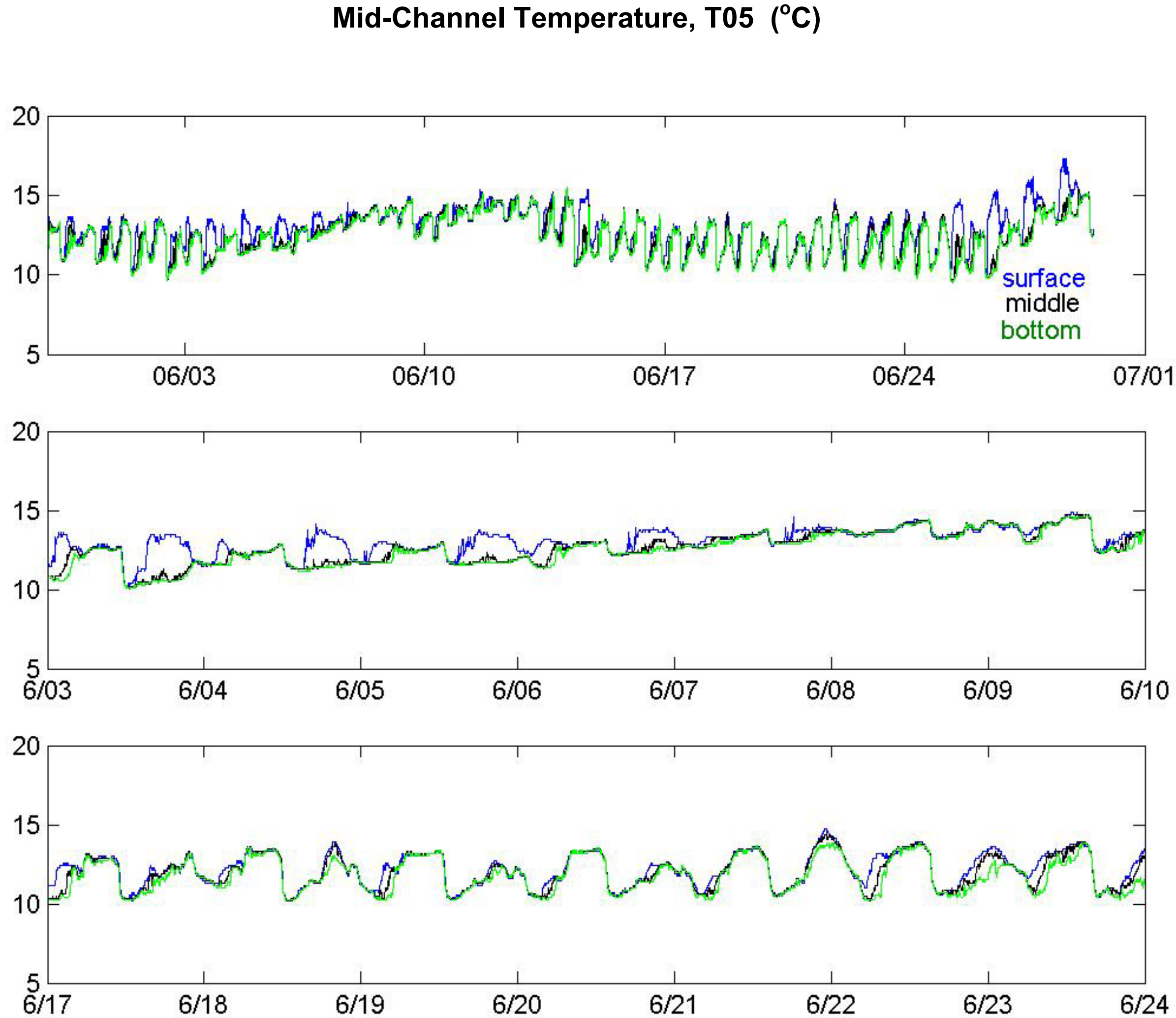


Figure 56. Temperature at mid-channel mooring, Spring 2003. Top: full record. Center: week of June 3-10. Bottom: week of June 17-24. Movement of warmed surface water out of the channel at ebb tide is more evident in the middle harbor than further down at Campbell Cove (e.g., June 4-7).

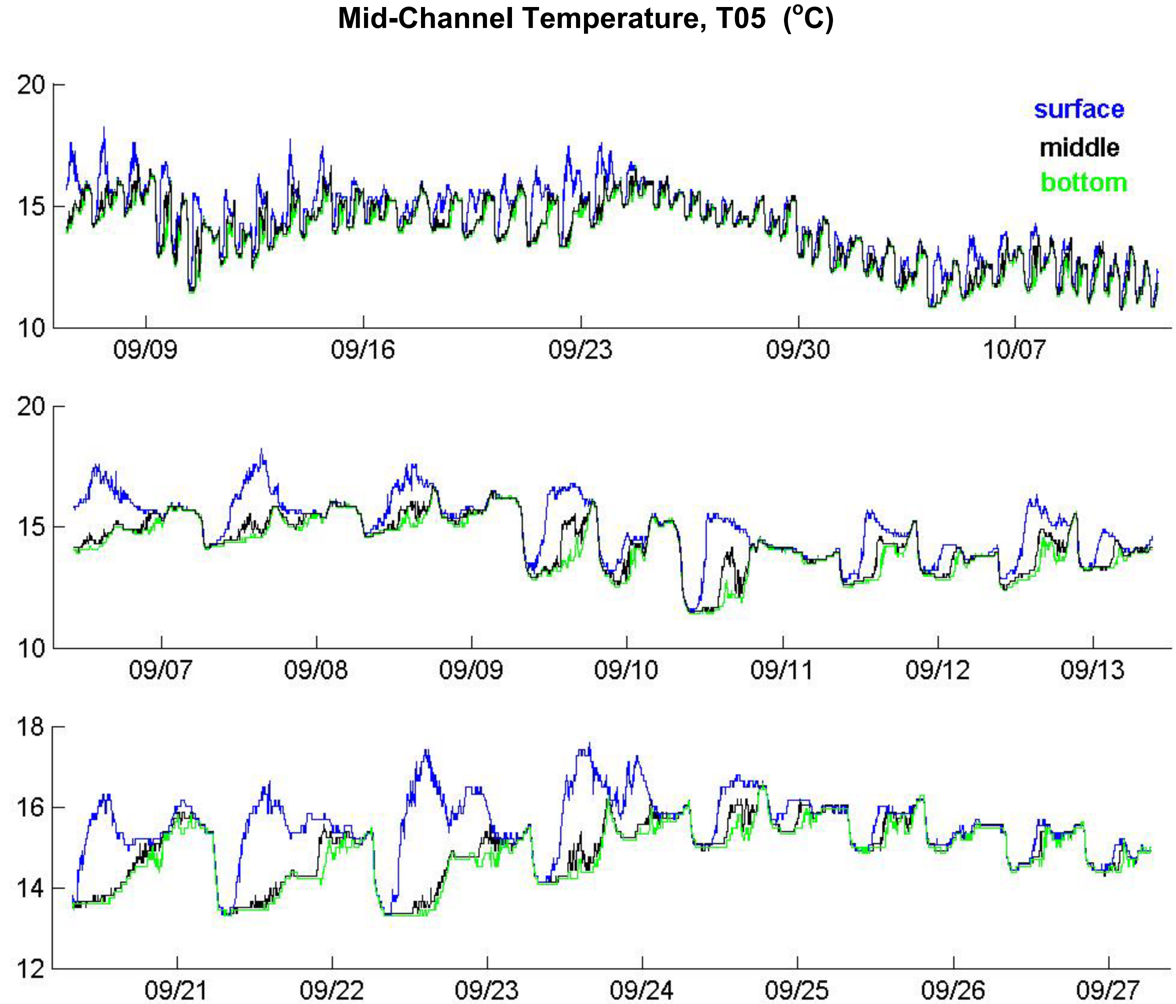


Figure 57. Temperature mid-channel mooring, Fall 2003. Top: full record. Center: week of September 7-13. Bottom: week of September 20-27. Strong surface warming events are frequent during the month of September. Blue surface water temperature curves show warmed surface water preceding sub-surface water during ebb tide outflows.

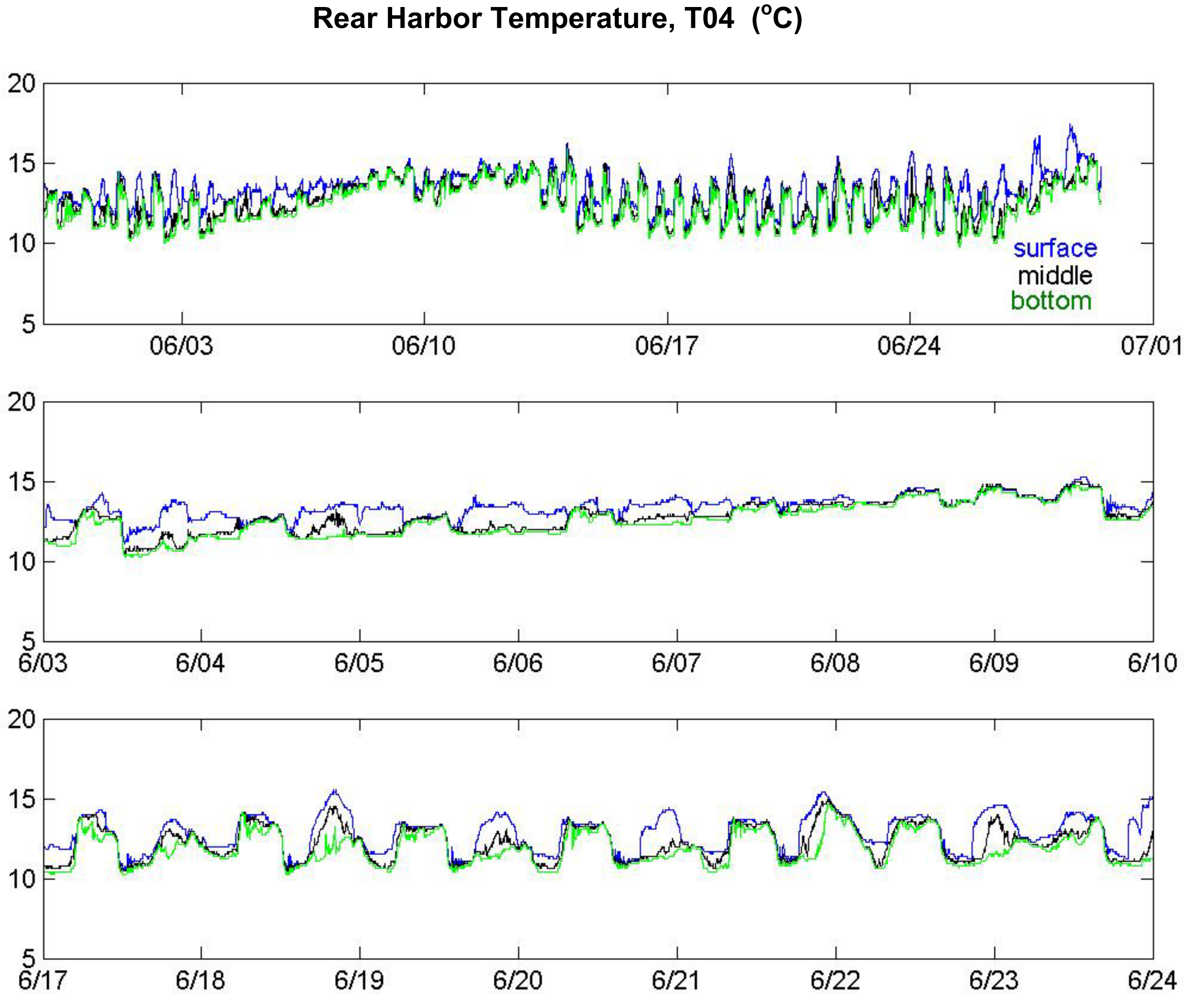


Figure 58. Temperature at rear harbor mooring (Porto Bodega), Spring 2003. Top: full record. Center: week of June 3-10. Bottom: week of June 17-24.

Rear Harbor Temperature, T04 (^oC)

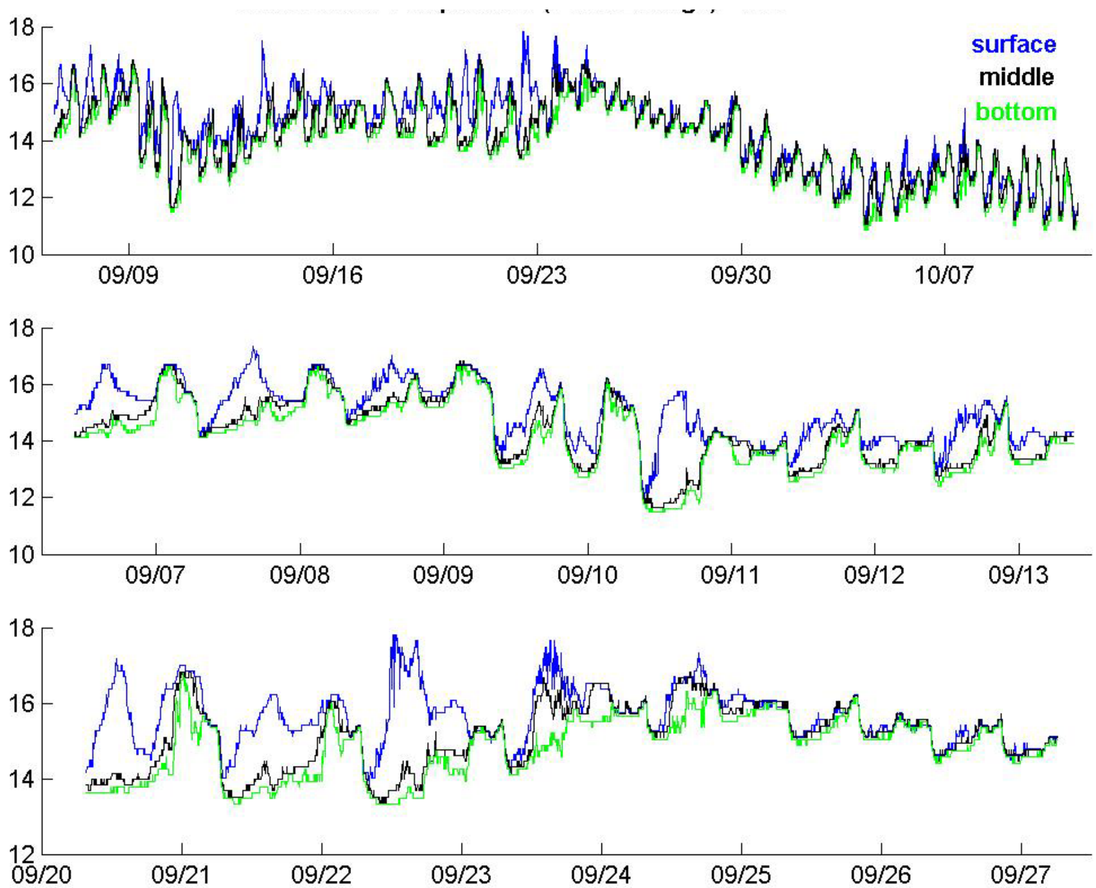


Figure 59. Temperature at rear harbor mooring (Porto Bodega), Fall 2003. Top: Full record. Center: Week of September 7-13. Bottom: week of September 20-27.

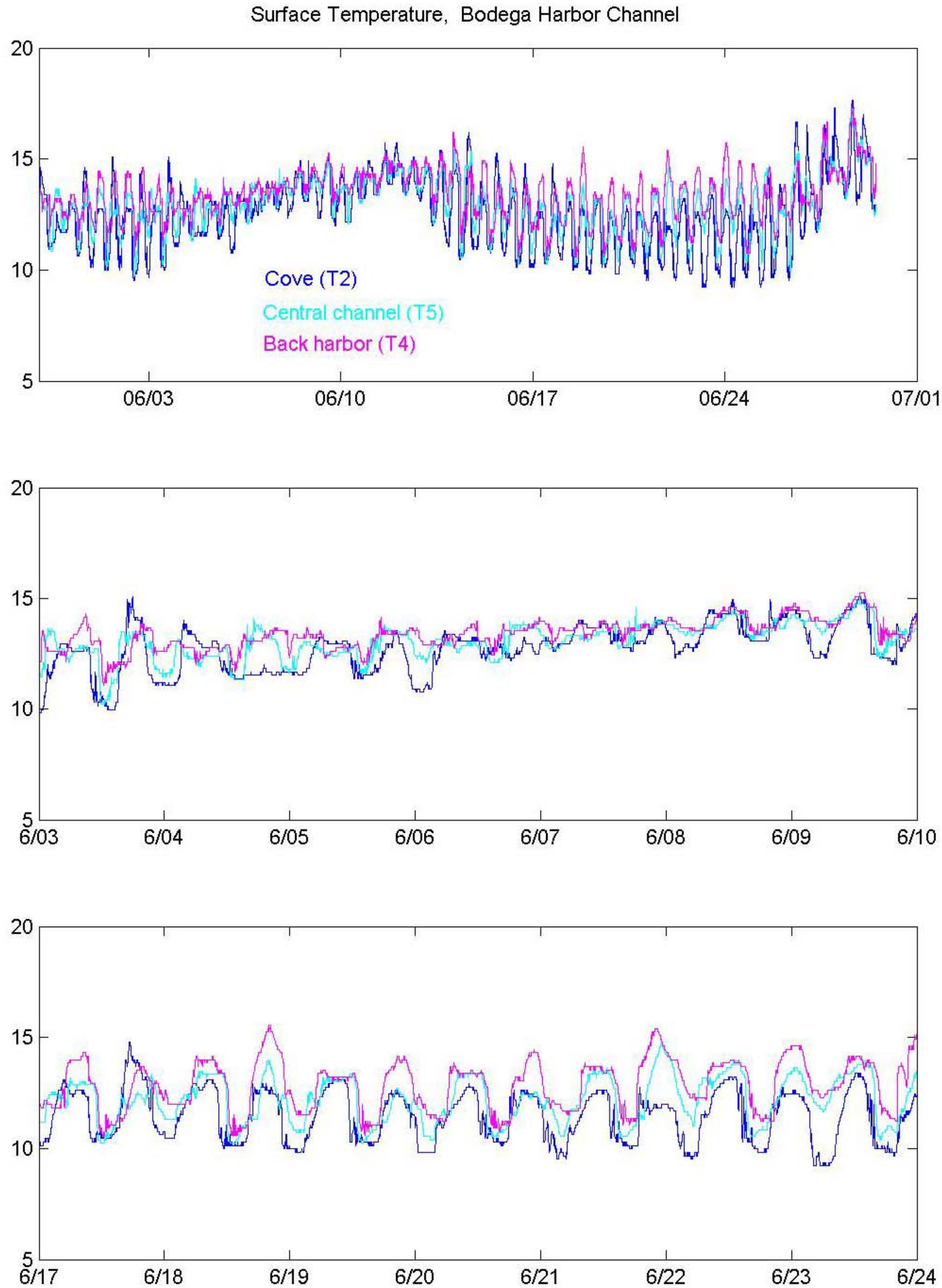
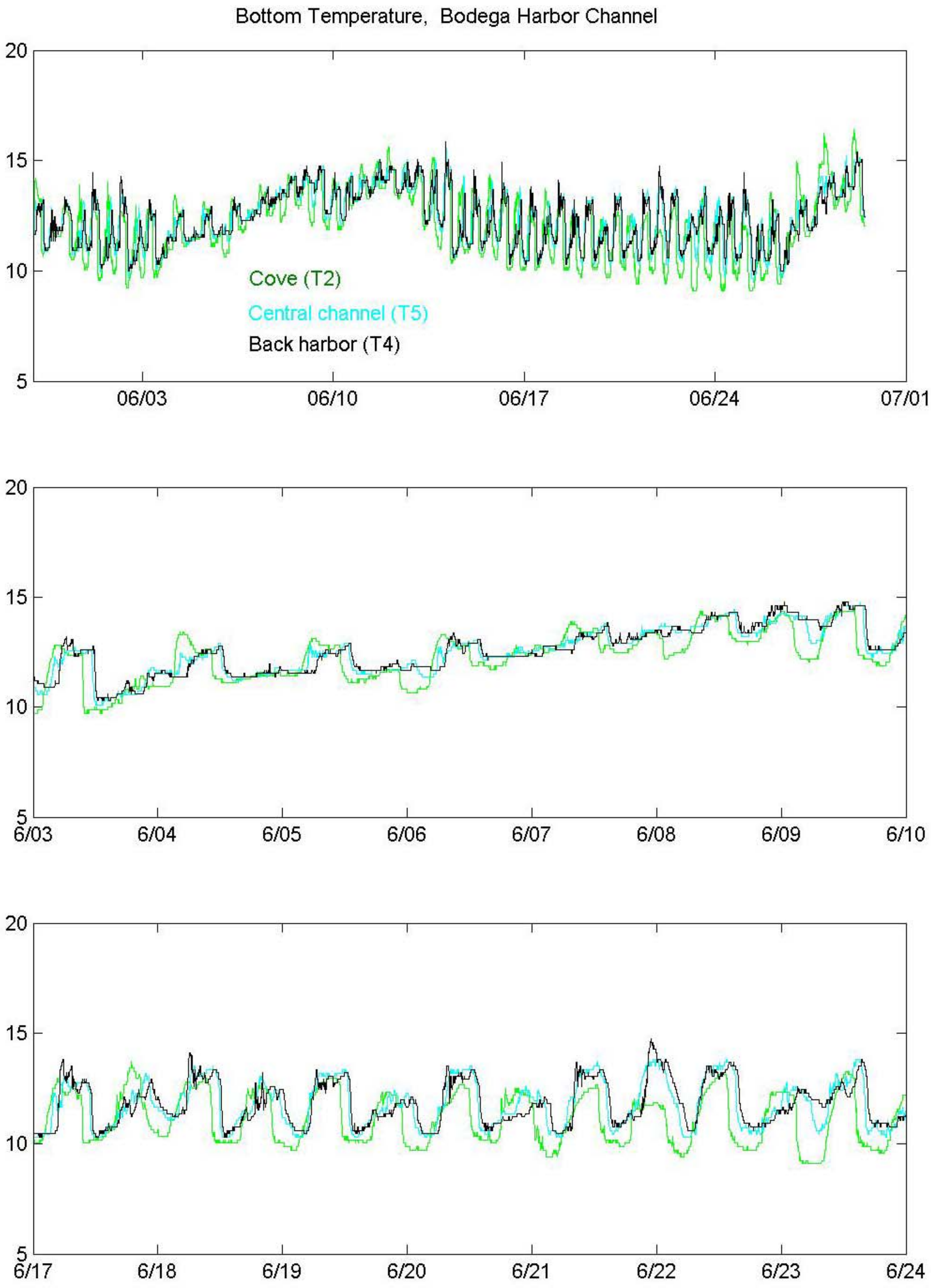


Figure 60. Surface temperatures at rear harbor, central channel and Campbell Cove, Spring 2003. Top: full record. Center: week of June 3-10. Bottom: week of June 17-24.

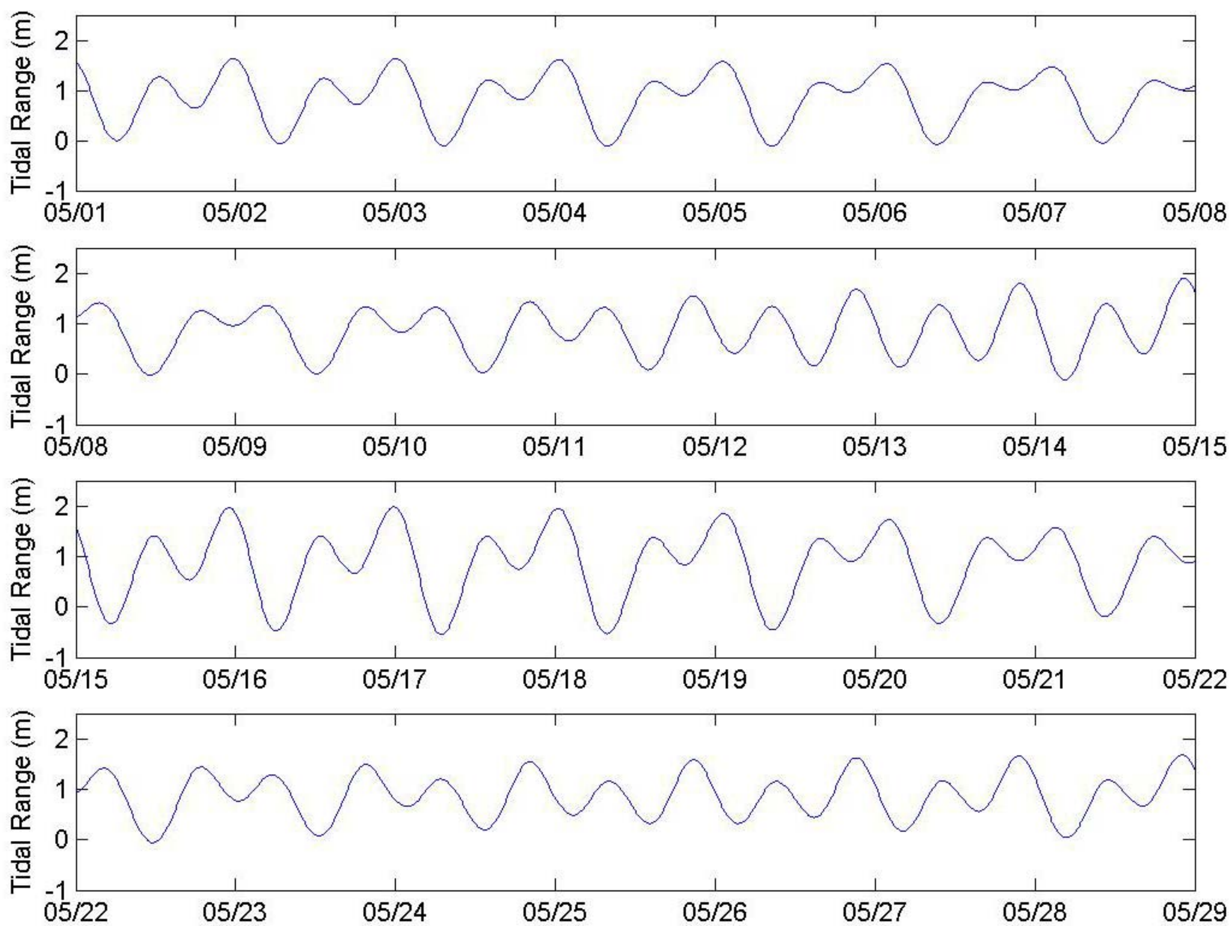


C

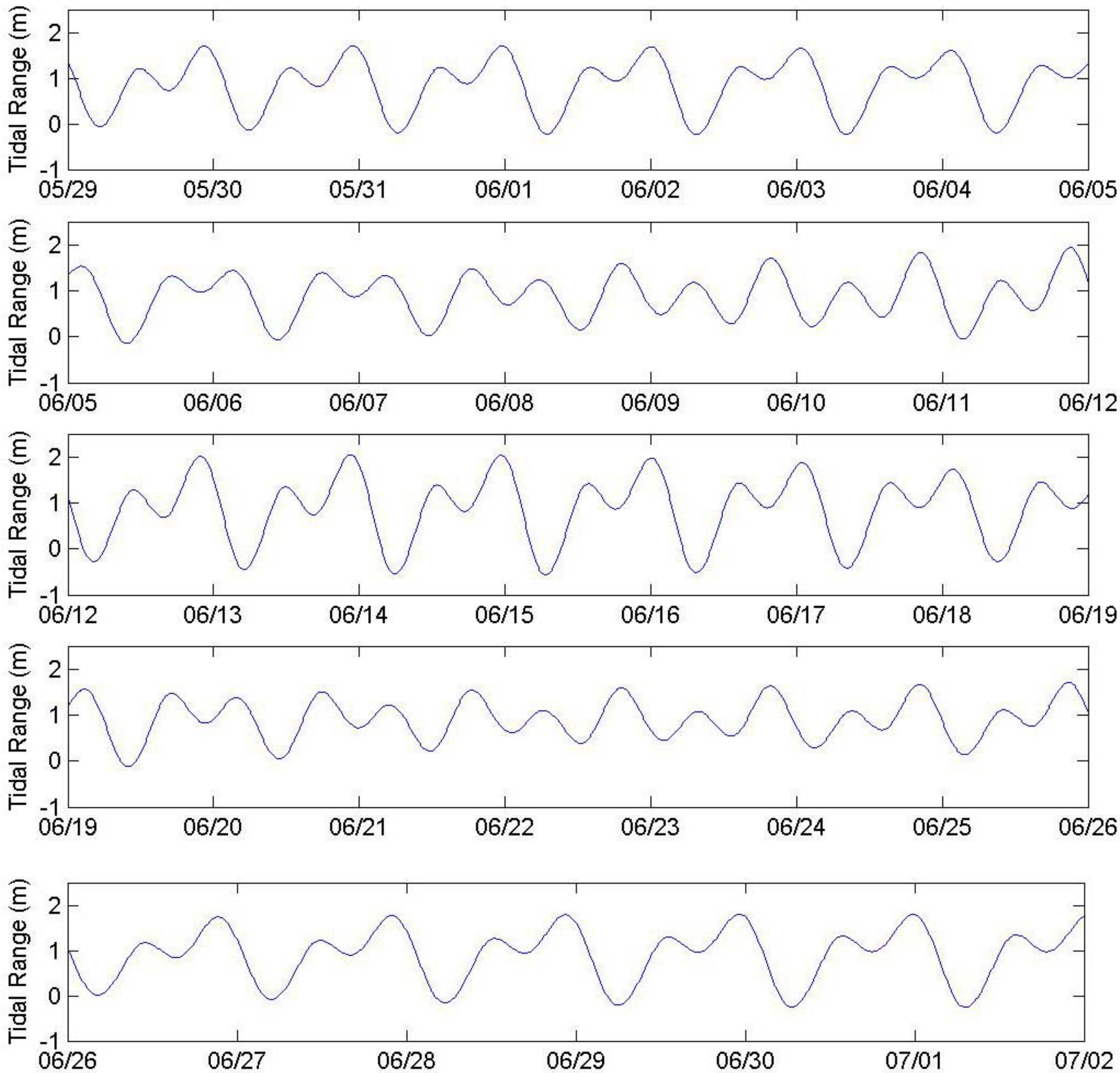
Figure 61. Bottom temperatures at rear harbor, central channel and Campbell Cove, Spring 2003. Top: full record. Center: week of June 3-10. Bottom: week of June 17-24.

APPENDIX: Tidal Records for Study Period

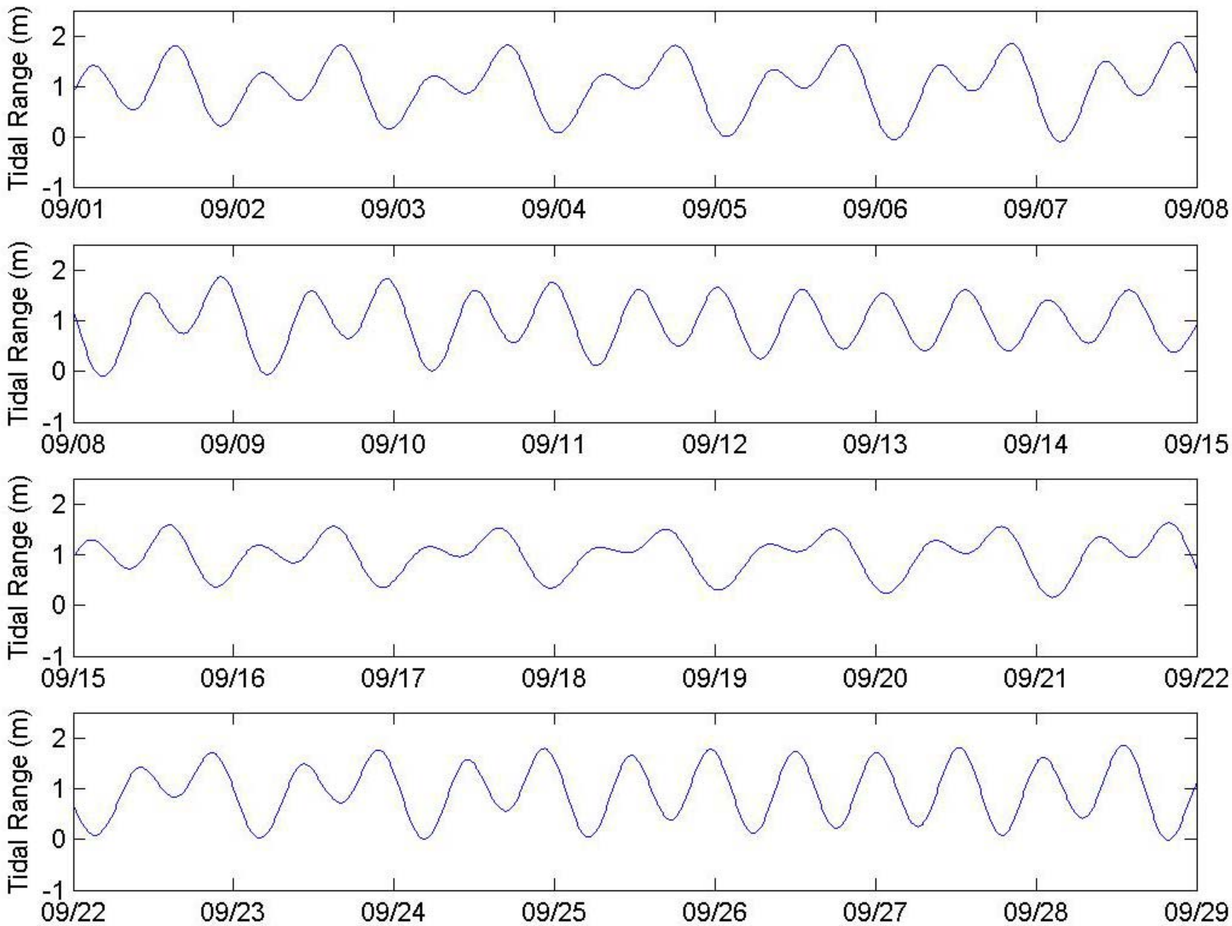
May 2003



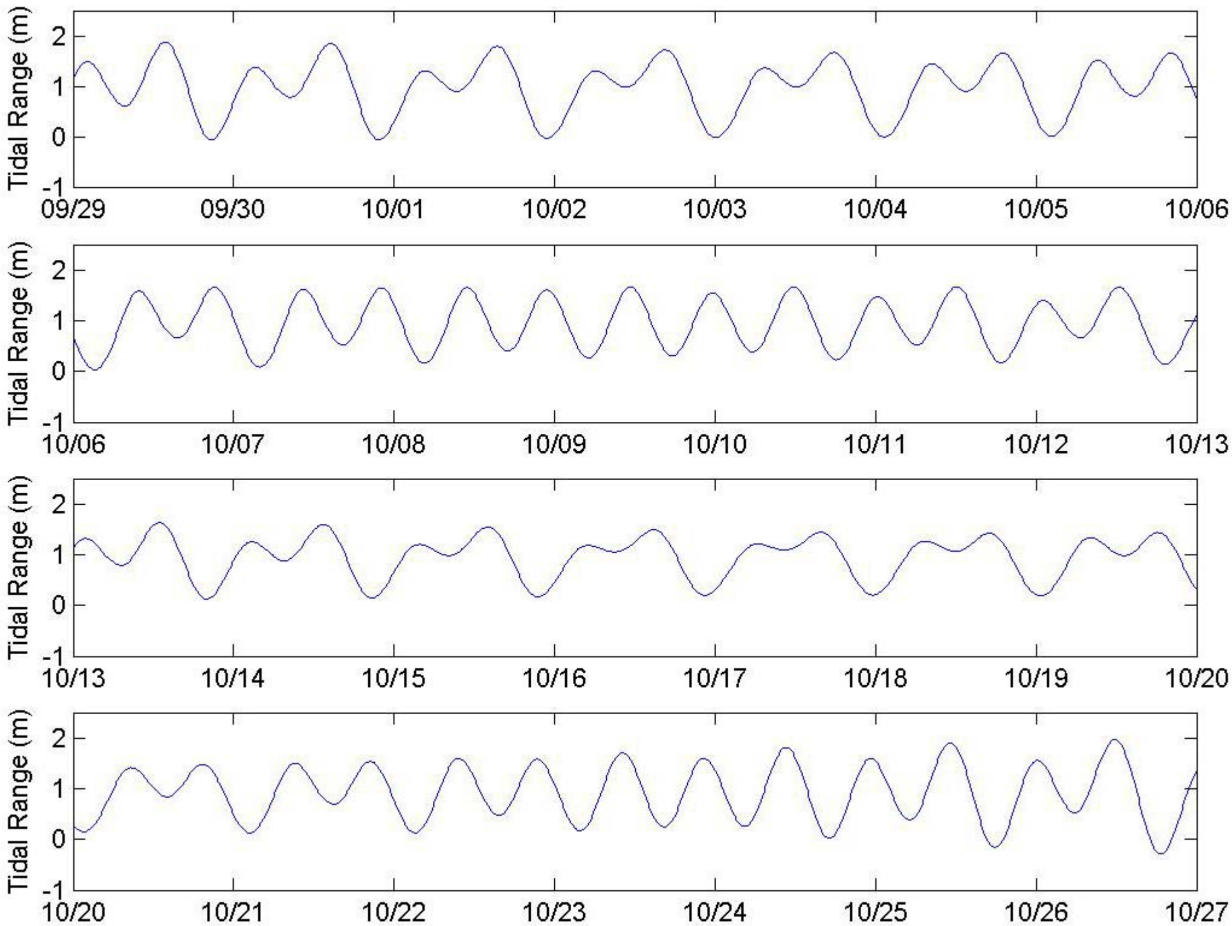
June 2003


Tidal Range (m)
2
1
0
-1
05/29
05/30
05/31
06/01
06/02
06/03
06/04
06/05
Tidal Range (m)
06/05
06/06
06/07
06/08
06/09
06/10
06/11
06/12
Tidal Range (m)
06/12
06/13
06/14
06/15
06/16
06/17
06/18
06/19
Tidal Range (m)
06/19
06/20
06/21
06/22
06/23
06/24
06/25
06/26
Tidal Range (m)
06/26
06/27
06/28
06/29
06/30
07/01
07/02

September 2003



October 2003



November 2003