Russian River Estuary Circulation and Water Quality

2012 Data Report

Report to
Sonoma County Water Agency (SCWA)

Prepared by

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1. Introduction

This report summarizes data collected in the Russian River Estuary during the summer and fall of 2012 by Bodega Marine Laboratory (BML) personnel under contract from the Sonoma County Water Agency (SCWA). The purpose of this study was to elucidate patterns and mechanisms of water circulation and stratification within the estuary, with particular interest toward salinity and dissolved oxygen (DO).

Data were collected during the months of May through November, which covers the portion of the year when river flow is at its lowest. Lower river flows increase the probability of an extended closure of the estuary to the ocean by allowing long-period ocean waves to build a sand bar across the estuary mouth. Separation from the ocean dramatically changes the physical forcing mechanisms in the estuary by removing or severely reducing the effect of tides as well as by preventing freshwater to flow out to the ocean. Both of these changes result in greater stratification within the estuary, which in turn can cause a reduction in dissolved oxygen at depth. The mouth exhibits a continuum of conditions from open (strongly tidal) to constricted (muted tides), perched (outflow only), and closed (zero flow).

To monitor patterns of water flow, two Acoustic Doppler Current Profilers (ADCPs) were deployed. These instruments use acoustics to construct a vertical profile of current velocities throughout the water column at pre-set time intervals, and were strategically placed in deep pools toward the mouth (Patty's Rock) and in the inner estuary (Heron Rookery). Additionally, boat-based conductivity/temperature/depth (CTD) surveys were conducted at a series of twelve sampling stations throughout the estuary on a regular basis. These surveys provided vertical profiles of salinity, temperature, dissolved oxygen (DO), chlorophyll fluorescence, and turbidity at each station. The timing of the deployments and CTD surveys are summarized in Figure 1.1 and Table 1.1, and the approximate locations of the ADCP deployments and CTD stations are marked on the map in Figure 1.2.

To supplement these efforts, the following additional tasks were performed:

- Water level data loggers were used to measure water level and temperature at high temporal resolution in various sections of the estuary.
- Salinity and temperature time series were recorded at multiple depths at both Patty's Rock and Heron Rookery using moored in-situ instruments.
- Wind speed and direction were measured near the estuary mouth and in the upper estuary (Freezeout Island).
- Biochemical oxygen demand (BOD) samples were taken at several locations throughout the estuary and analyzed in the laboratory.

Several events occurred in 2012 that resulted in reduced interaction of the estuary with the ocean, including an extended period of perched conditions in June and July as well as brief closure events in late September, October, and November. These events caused increased density stratification and reduction of DO at depth, particularly in the inner estuary. The remainder of this report summarizes the data collected.

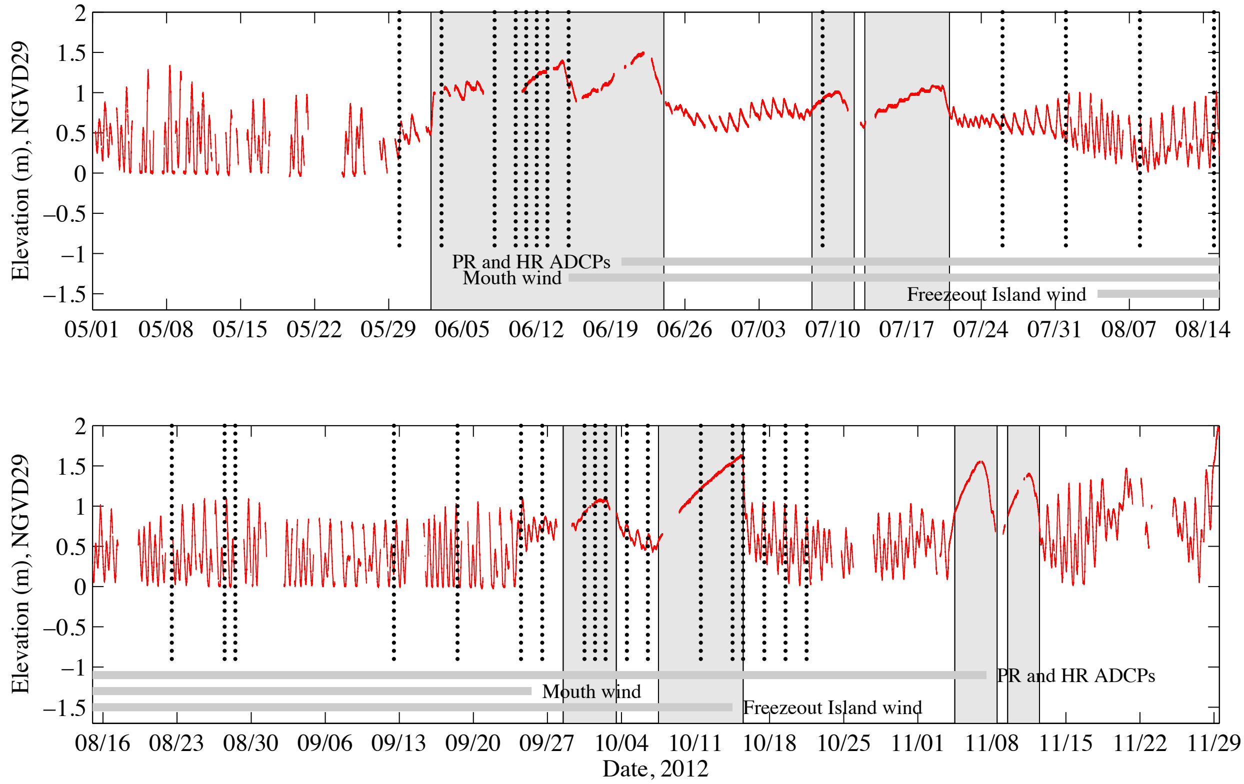

Figure 1.1 Timeline indicating water level at Jenner during the 2012 study season. CTD transects are indicated by vertical dotted lines, and deployments of ADCPs at Patty's Rock (PR) and Heron Rookery (HR) as well as wind sensor deployments are indicated by horizontal gray lines. Perched periods and closures are indicated by vertical gray bars.

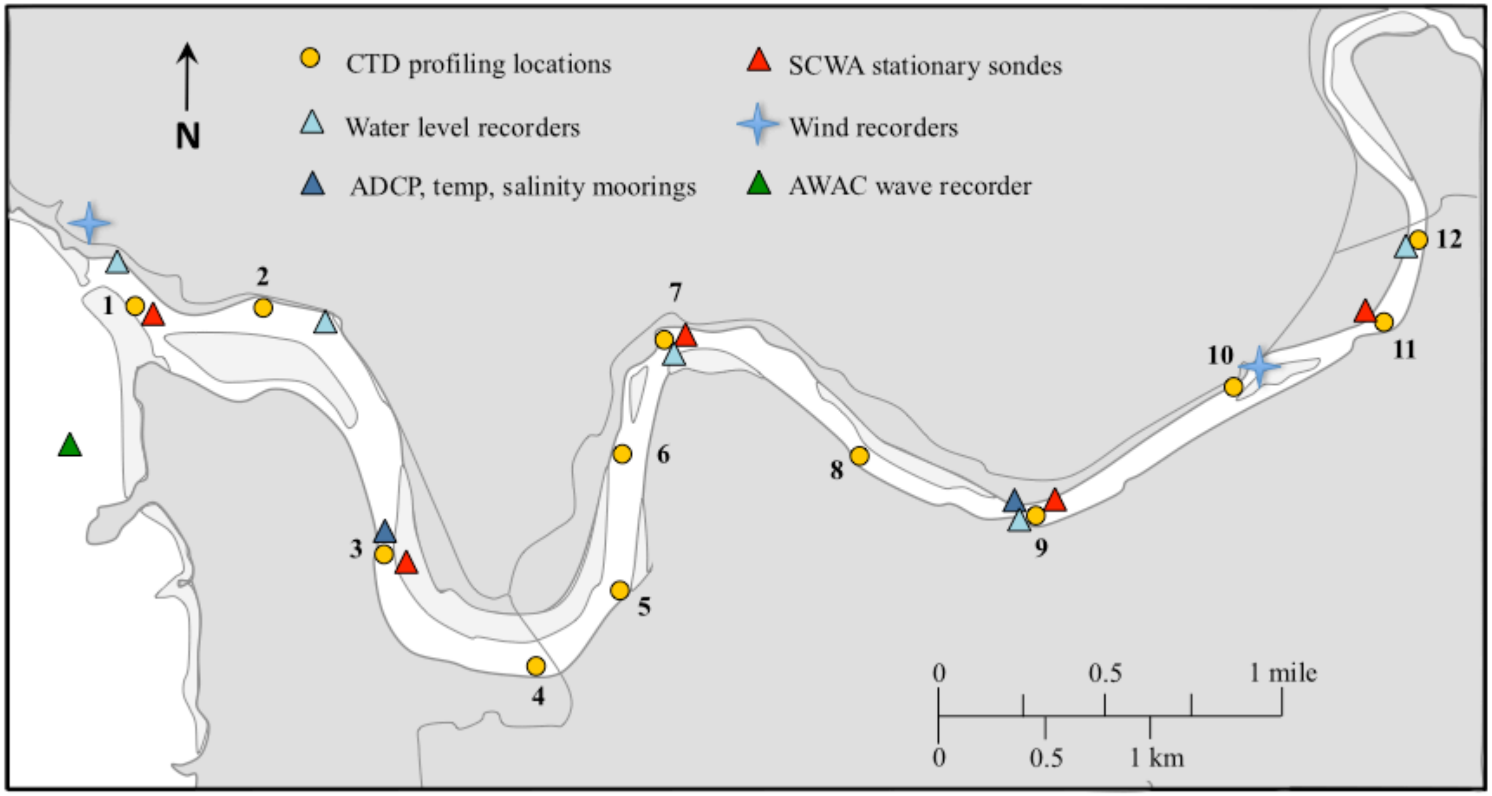

Figure 1.2 Map of the Russian River Estuary depicting the approximate locations of data collection in 2012.

Table 1.1 Summary of data collection locations and dates.

Station No. (Fig 1.2)	Station Name	Data Collection	Approx. Location	Installation Date	Recovery Date
1	"Mouth"	Temp/WL*	38.45121 N 123.12698 W	6/13/2012	9/19/2012
		CTD	38.450056 N 123.126883 W	--	--
1	"Mouth Camera"	Wind	38.45269 N 123.12718 W	6/15/2012	9/26/2012
2	"Penny Island"	CTD	38.450000 N 123.118519 W	--	--
3	"Patty's Rock"	CTD/BOD	38.439431 N 123.111656 W	--	--
		ADCP/WL*	38.439431 N 123.111656 W	6/20/2012	11/8/2012
		Salinity/temp	38.439431 N 123.111656 W	6/20/2012	11/8/2012
4	"Bridgehaven"	CTD	38.434181 N 123.106194 W	--	--
5	"Willow Creek"	CTD/BOD	38.437090 N 123.097855 W	--	--
6	"Flats"	CTD	38.441228 N 123.098249 W	--	--
7	"Sheephouse Creek"	CTD/BOD	38.448496 N 123.095716 W	--	--
		Temp/WL*	38.44893 N 123.09602 W	7/16/2012	11/8/2012
8	"Osprey Rookery"	CTD	38.444066 N 123.085145 W	--	--
9	"Heron Rookery"	CTD/BOD	38.440674 N 123.074972 W	--	--
		ADCP/WL*	38.440674 N 123.074972 W	6/20/2012	11/8/2012
		Salinity/temp	38.440674 N 123.074972 W	6/20/2012	11/8/2012
10	"Freezeout Island"	CTD	38.446907 N 123.060572 W	--	--
		Wind	38.44617 N 123.06092 W	7/25/2012	10/15/2012
11	"Freezeout Creek"	CTD	38.448858 N 123.052847 W	--	--
12	"Moscow Bridge"	CTD	38.453672 N 123.049217 W	--	--
		Temp/WL*	38.45385 N 123.04921 W	7/16/2012	11/14/2012

* WL: "water level," as determined from pressure sensor readings

2. Water Level Measurements

To accurately record water surface elevation in the estuary, U20-model HOBO Water Level Loggers (Onset Computer, Inc.) were deployed at the estuary mouth, Sheephouse Creek, Heron Rookery, and Moscow Bridge (refer to Table 1.1 for deployment dates by location). Water level was also recorded at the Jenner Visitor Center by the SCWA gauge and at Patty's Rock and Heron Rookery by the ADCPs. The HOBO loggers and Visitor Center gauge measured water level every two minutes, while the ADCPs sampled every ten minutes. These measurements served to allow examination of tides and wind seiches moving through the estuary as well as to provide a time series of water surface elevation in order to translate the instrument depth to actual elevations.

In order to convert pressure measured by the loggers into meaningful elevations, raw output was corrected for changes in atmospheric pressure using barometer data measured at Bodega Marine Laboratory as part of the Bodega Ocean Observing Node (BOON). Barometric pressure was measured at 30s intervals then averaged into 1-min data, which was then cleaned using a rate-of-change filter to remove points resulting in a rate of change greater than 0.5 millibar per minute (mbar/min). Data points were matched in time, and barometric pressure was then subtracted from pressure measured by the instrument in order to obtain water pressure. Water pressure was converted to depth using density that was calculated using temperature measured by the logger and an assumed average salinity 16.5 PSU (error due to fluctuations in salinity and thermal stratification is less than 1%). To convert depth to elevation, the instruments were corrected to match the SCWA gauge at Jenner between 2am and 8am (local time) on 2 October 2012, a time when winds were very light, the estuary mouth was closed, and flow into the estuary was low (less than 120 cfs). The error in the relative elevation time series is expected to be less than 2-3 cm.

Water levels also indicate periods when the estuary is closed, perched, or constricted. When the barrier beach at the mouth causes closure or perched conditions, water levels rise monotonically as freshwater is added to the estuary from the river at a faster rate than water is flowing over or through the sand at the mouth. When the mouth is constricted, the tidal signal in water level becomes muted (low tides become less low, high tides become less high) due to increased friction.

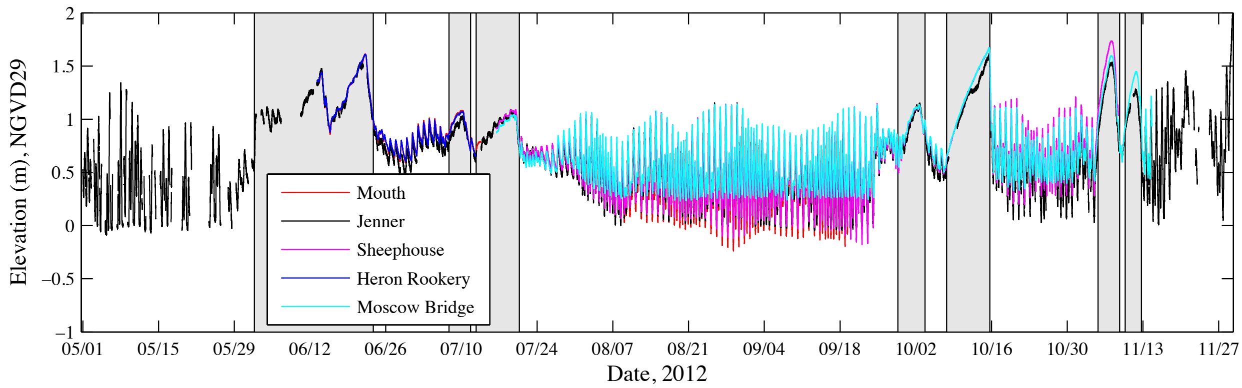

Figure 2.1 Water surface elevation derived from pressure readings taken at the mouth (red line), Jenner (black line), Sheephouse Creek (magenta line), Heron Rookery (blue line), and Moscow Bridge (cyan line). Gray bars indicate perched periods and closures.

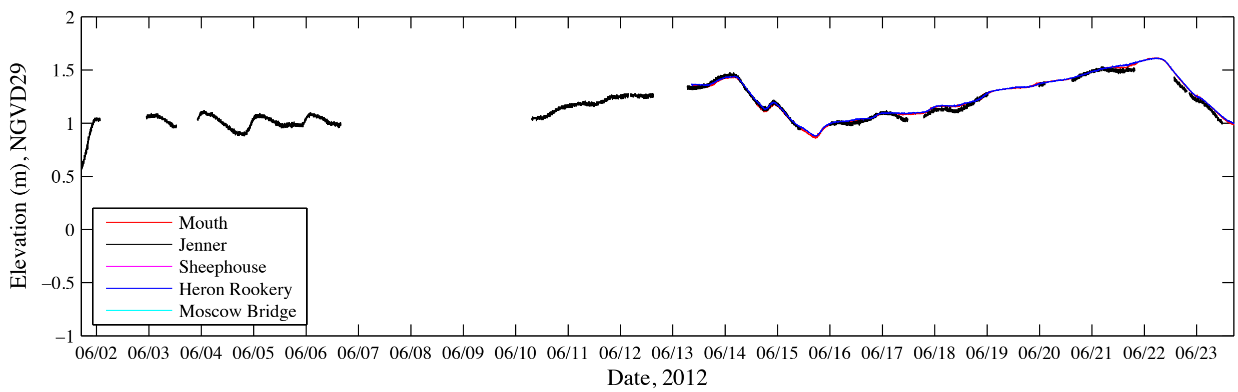

Figure 2.2 Water surface elevation derived from pressure readings taken at the mouth (red line), Jenner (black line), and Heron Rookery (blue line) during perched conditions in June 2012.

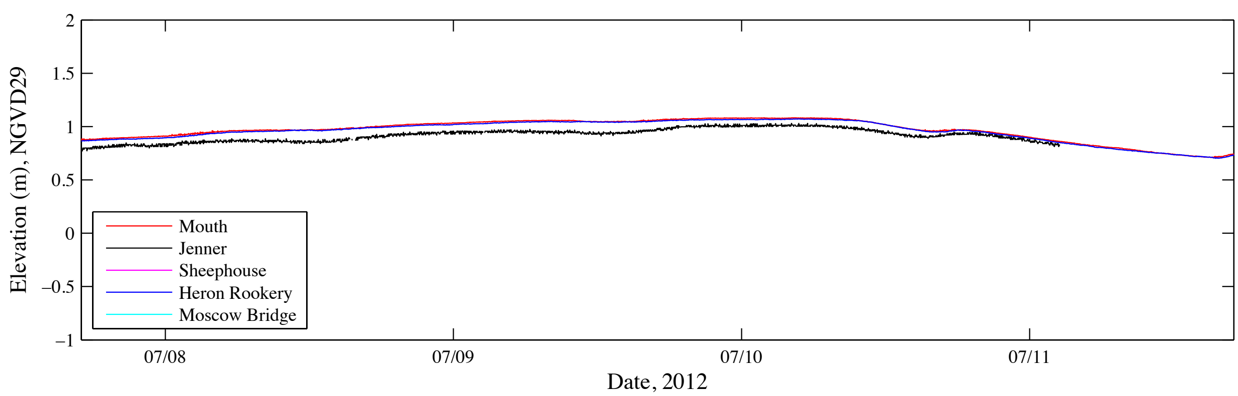

Figure 2.3 Water surface elevation derived from pressure readings taken at the mouth (red line), Jenner (black line), and Heron Rookery (blue line) during perched conditions in July 2012.

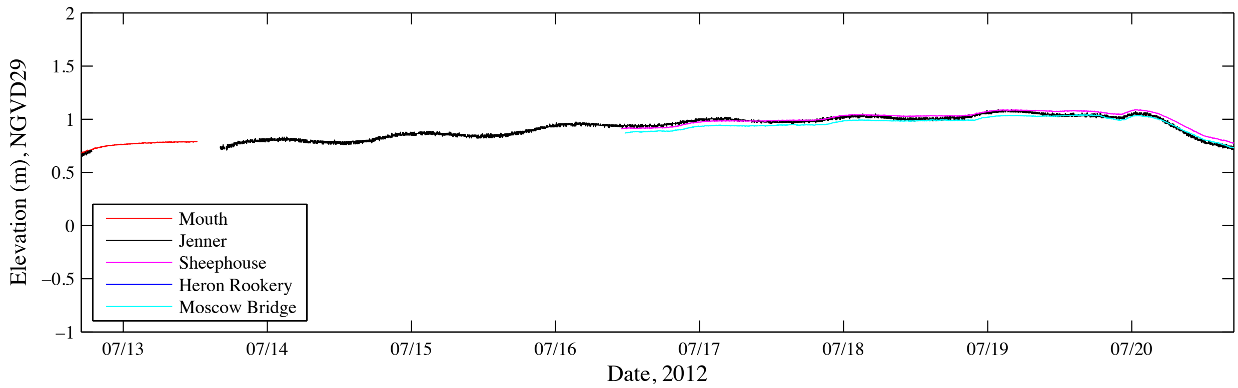

Figure 2.4 Water surface elevation derived from pressure readings taken at the mouth (red line), Jenner (black line), Sheephouse Creek (magenta line), and Moscow Bridge (cyan line) during perched conditions in July 2012.

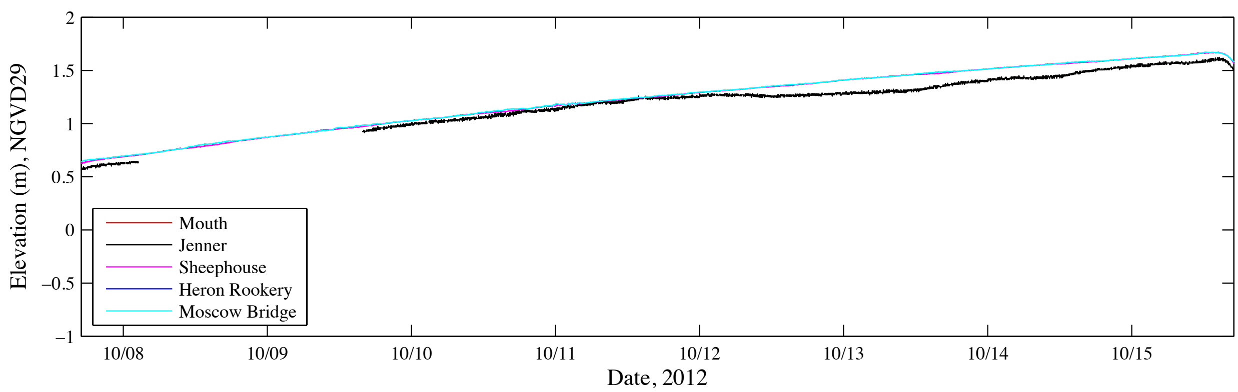

Figure 2.5 Water surface elevation derived from pressure readings taken at Jenner (black line), Sheephouse Creek (magenta line), and Moscow Bridge (cyan line) during the closure period from 7-15 October 2012.

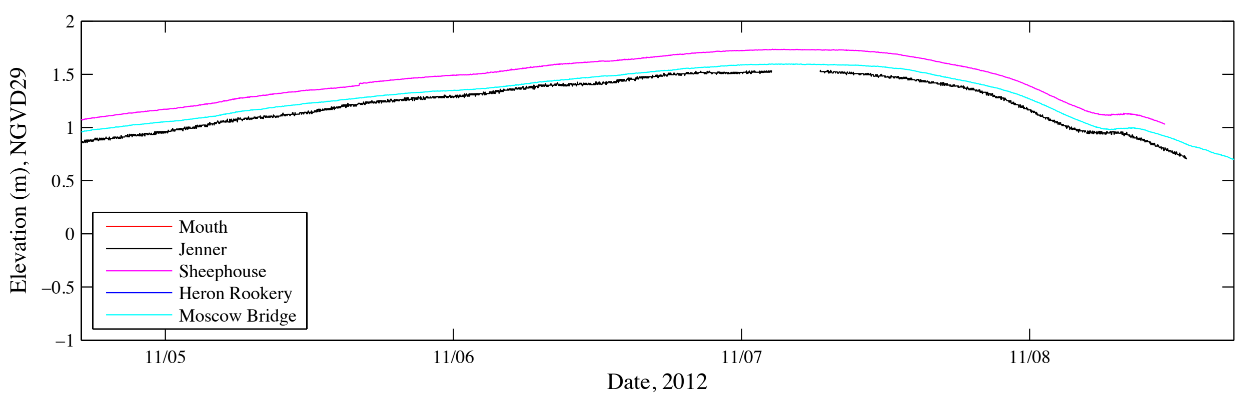

Figure 2.6 Water surface elevation derived from pressure readings taken at Jenner (black line), Sheephouse Creek (magenta line), and Moscow Bridge (cyan line) during the closure period from 4-8 November 2012.

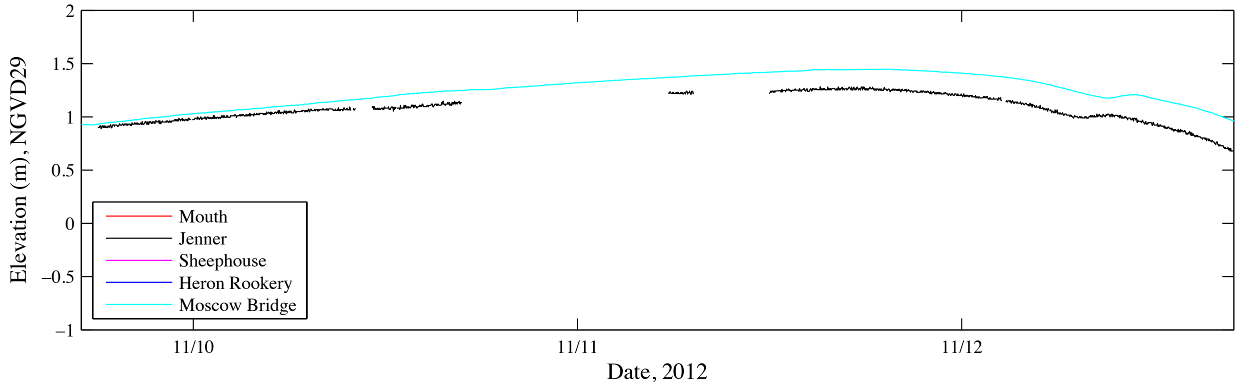

Figure 2.7 Water surface elevation derived from pressure readings taken at Jenner (black line), Sheephouse Creek (magenta line), and Moscow Bridge (cyan line) during the closure period from 9-12 November 2012.

3. Biochemical Oxygen Demand

Water samples were taken from several sites throughout the estuary in order to monitor biochemical oxygen demand (BOD). At each station, samples were taken from the surface, near the halocline (the depth at which the vertical salinity gradient is strongest), and near the bottom. Samples were incubated for 5 days following the standard procedures for BOD sample processing, and the resulting BOD_5 number represents the concentration of oxygen (in mg/L) that was used by microorganisms to oxidize the organic material present in the sample.

A peak in BOD_5 occurred in mid- to late-September, particularly near the bottom (Figure 3.1). In the inner estuary (at Heron Rookery), BOD_5 levels were greatest near the bottom in the saltwater layer. Little difference was seen between surface and bottom BOD_5 at Freezeout Creek, likely because the water column is well mixed in that location. In the middle to outer estuary (at Sheephouse Creek and Patty's Rock), mean BOD_5 was higher near the halocline (Figure 3.2). The largest within-site difference in BOD_5 was at Willow Creek, where the "bottom" sample was taken immediately after stirring sediment into the water column with a paddle (Figure 3.2).

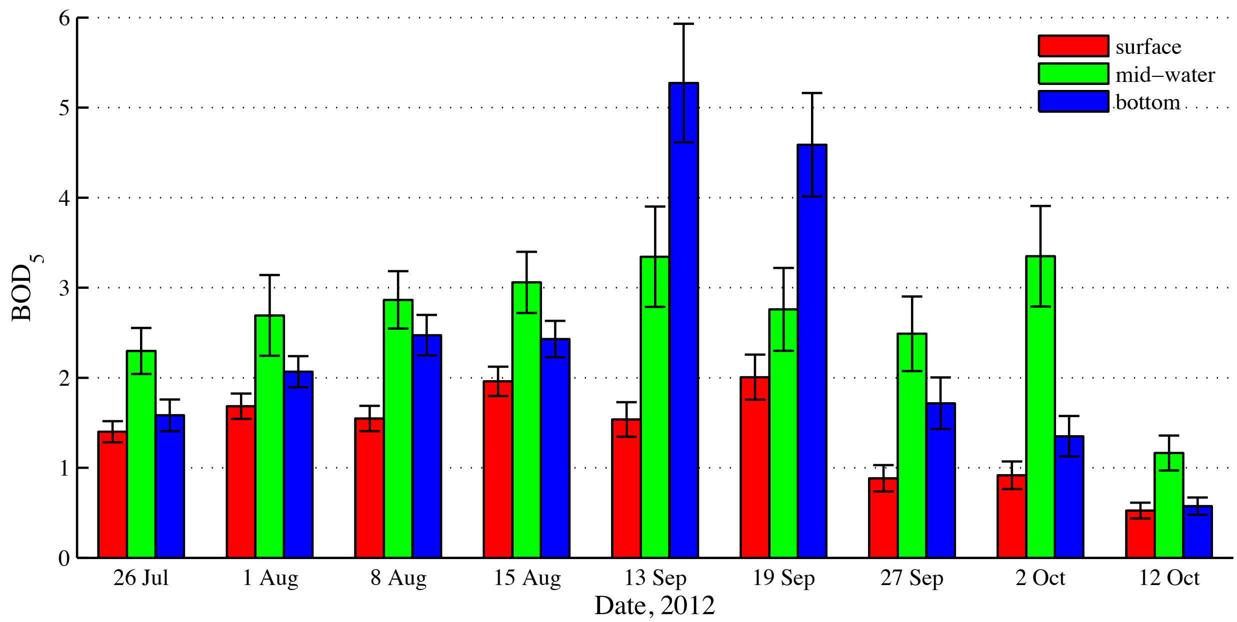

Figure 3.1 Bar chart showing mean BOD_5 at each depth and date for all stations. Surface data are red, data from the halocline (mid-water) are green, and near-bottom data are blue. Error bars represent the standard error of the means.

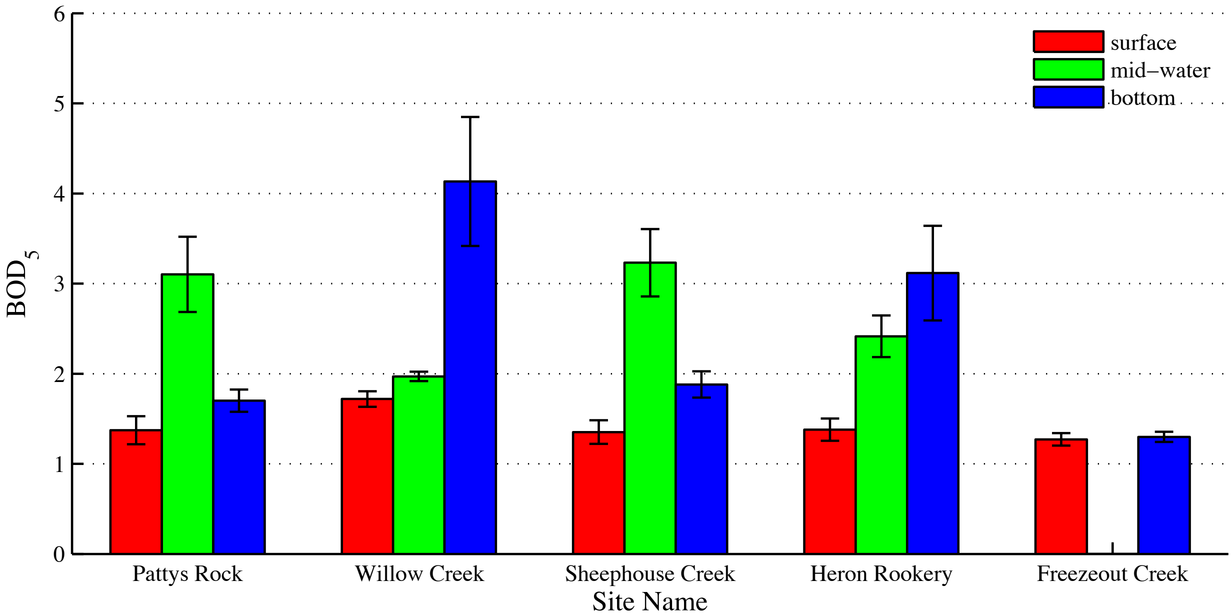

Figure 3.2 Bar chart showing mean BOD_5 at each station and depth for all dates. Surface data are red, data from the halocline (mid-water) are green, and near-bottom data are blue. Note that the "bottom" Willow Creek station was manually stirred with a paddle prior to taking the water sample in order to incorporate bottom sediments into the sample. Also note that no mid-water samples were taken at Freezeout Creek due to the lack of salinity stratification at that site. Error bars represent the standard error of the means.

4. Photographic Record of Mouth State

A camera with an unobstructed view of the estuary mouth takes two photographs hourly between 8am and 6pm local time. During 2012, the camera took 7792 images on 363 separate days. These images serve as a record of the state of the mouth (see Figure 4.1) as well as the specific morphology of the beach and channel.

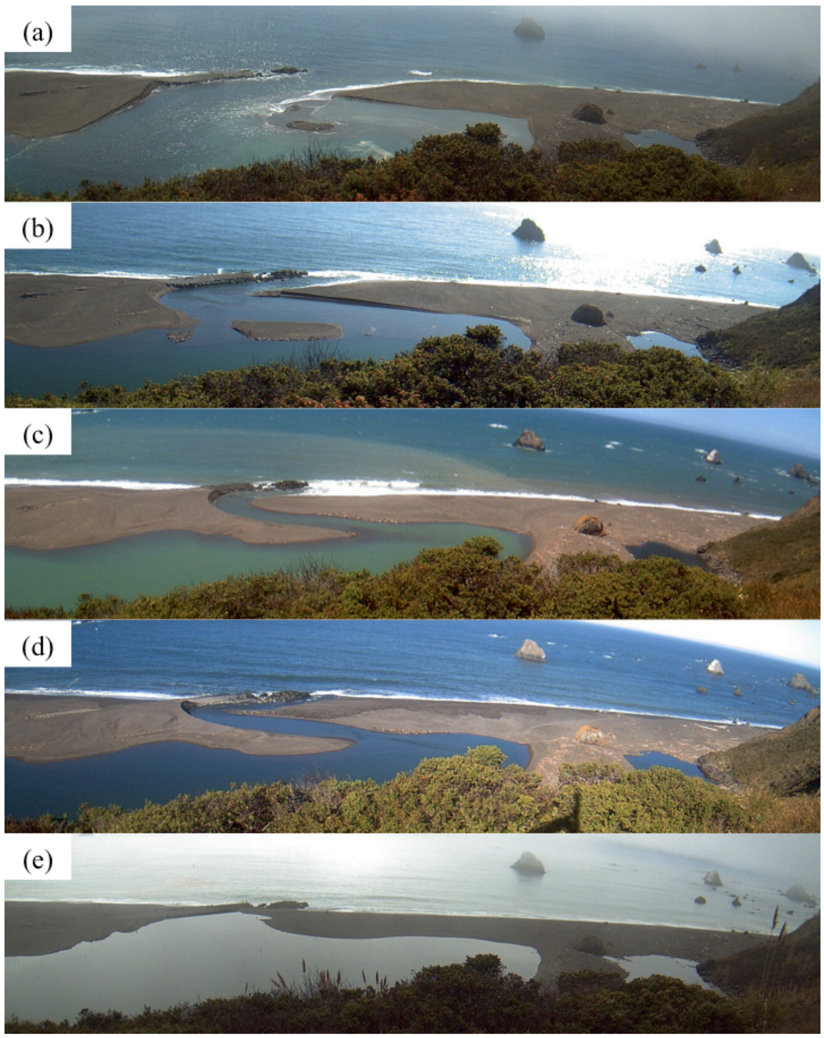

Figure 4.1 Sample images from the Russian River mouth camera. These images show examples of several morphological states including open (a: 21 August 2012), semi-constricted (b: 30 July 2012), constricted (c: 5 July 2012), perched (d: 10 June 2012), and closed (e: 9 October 2012).

5. Waves

Deep-water wave parameters were obtained from National Data Buoy Center (NDBC) Buoy 46214 (cdip.ucsd.edu/?nav=historic&sub=data&stn=029&stream=p1), which is operated by the Coastal Data Information Program (CDIP) and is located approximately 62 km southwest of the estuary mouth. Deep-water waves differ from waves that make contact with the beach at the estuary mouth because refraction occurs as the waves shoal and interact with shelf bathymetry, but these data can still provide useful information about the regional wave climate leading up to closure events. Additionally, a Nortek acoustic waves and currents (AWAC) meter was deployed near Goat Rock from 31 August 2012 until 15 November 2012. This instrument recorded wave height, direction, and period near the estuary mouth, which provided a link between offshore buoy data and the local wave climate.

Data from the AWAC deployment show strong agreement with offshore wave data in general (Figure 5.1). Waves measured at the AWAC were slightly smaller in height and the direction was rotated such that the waves were approaching the beach nearly perpendicular, as is expected based on wave refraction.

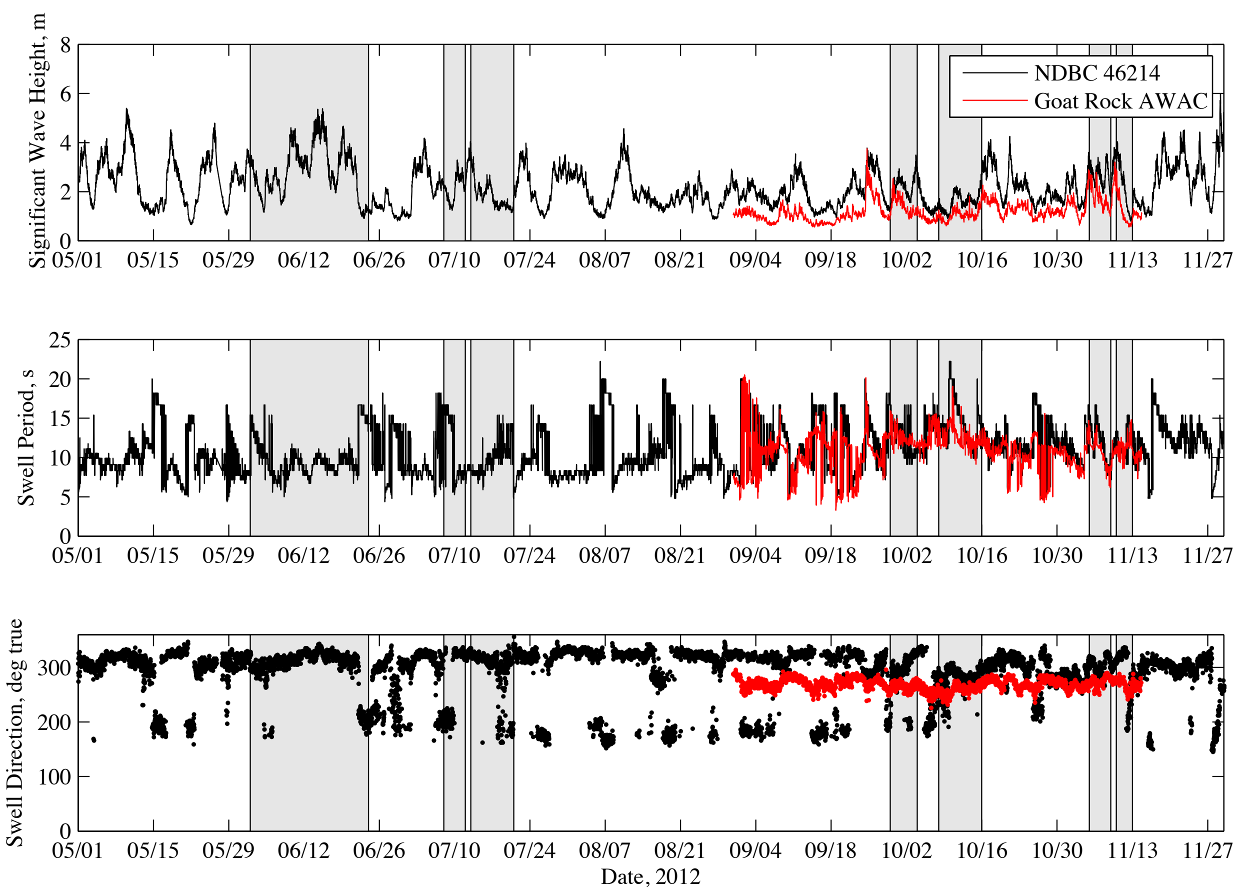

Figure 5.1 Significant wave height (top panel), peak swell period (middle panel) and dominant swell direction (bottom panel) from NDBC buoy 46214 (black) and the AWAC instrument (red). Gray bars indicate perched conditions and closure periods.

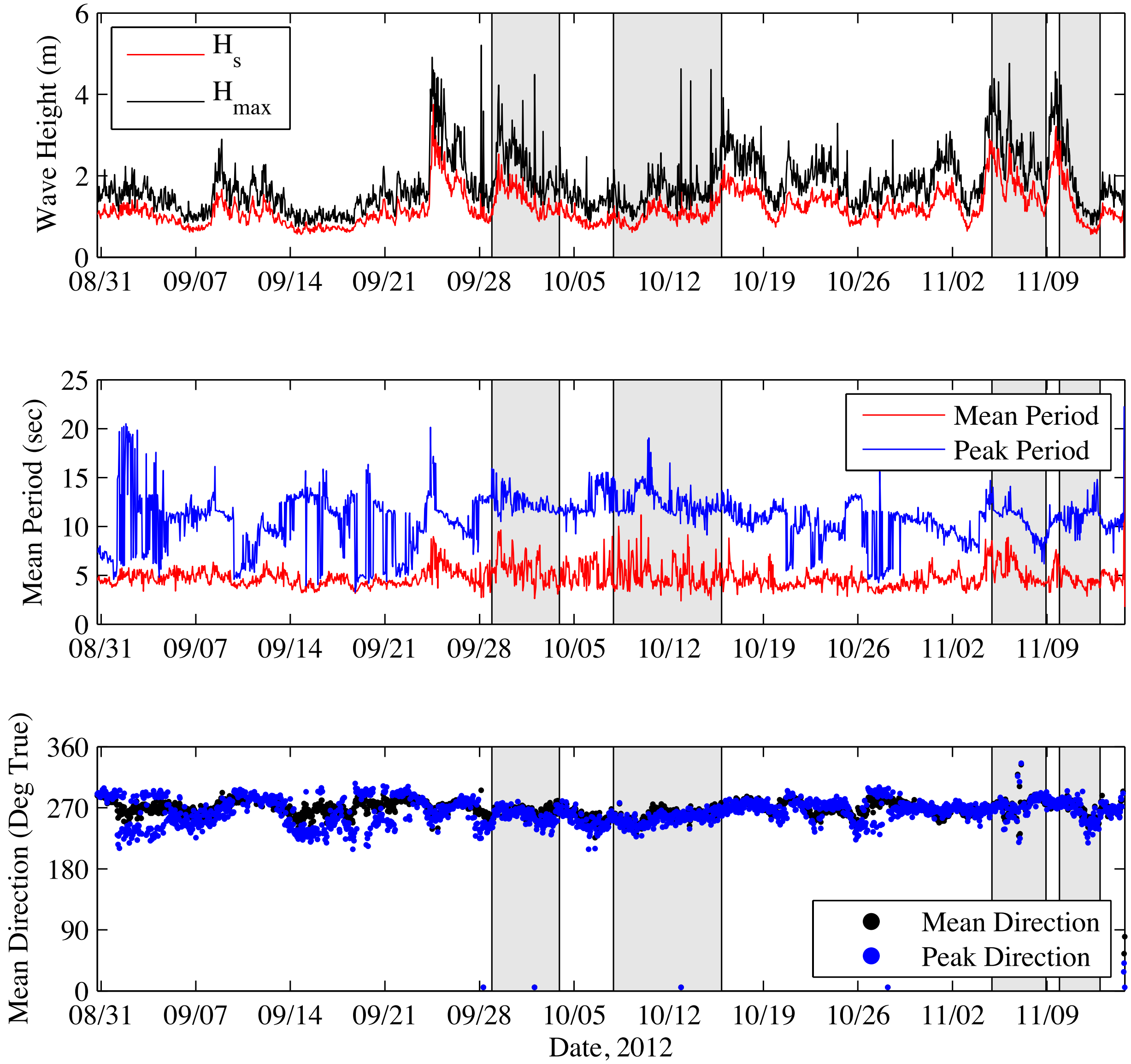

Figure 5.2 Significant (red line) and hourly maximum (black) wave height (top panel), mean (red line) and peak (blue line) swell period (middle panel) and mean (black dots) and dominant (blue dots) swell direction (bottom panel) from the AWAC instrument near Goat Rock. Gray bars indicate perched conditions and closure periods.

6. Wind

Two Davis anemometers were deployed in the Russian River estuary during the 2012 study season, one at the location of the camera overlooking the mouth, and the other at the seaward tip of Freezeout Island (refer to Table 1.1 for deployment dates by location). The data from these sensors show the presence of a diurnal sea breeze at both sites (Figures 6.1, 6.2). Furthermore, the data also show that the strength of the sea breeze is not consistent from one day to the next, nor is it consistent by location. On some days the wind was stronger at the mouth, and on others it was stronger at Freezeout Island (Figure 6.2).

The Freezeout Island anemometer is situated on the seaward tip of the island, with a thick stand of willow trees just landward of the anemometer. For this reason, the sensor was blocked to winds blowing from the land. This type of wind, known as the "land-breeze" is typically weaker than typical afternoon winds blowing from the direction of the sea, known as the "sea-breeze."

All wind velocity (direction and magnitude) data were decomposed into the along- and cross-channel components, which were determined based on the direction of the main axis of the estuary at each location. Cross-channel winds were very weak, and therefore only along-channel velocities are reported here as the landward wind velocity.

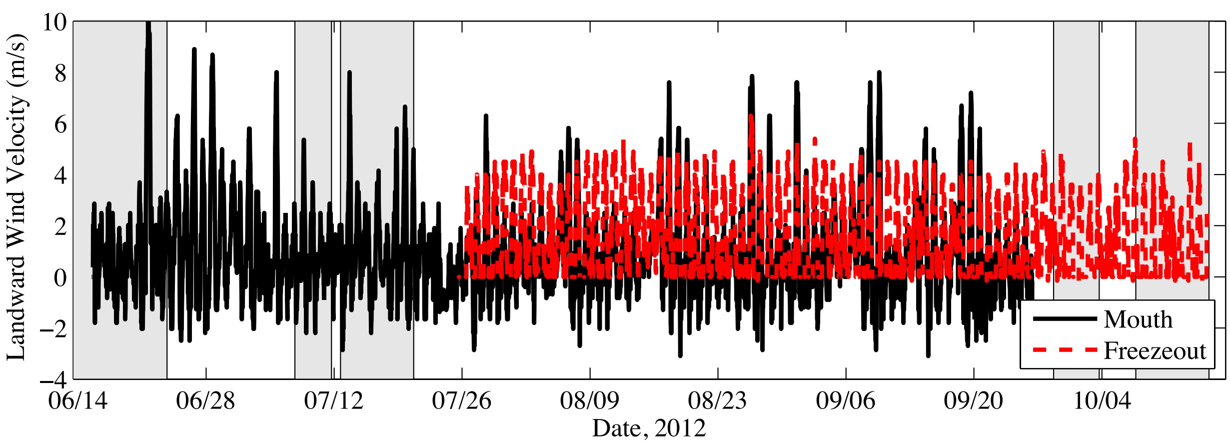

Figure 6.1 Landward component of wind velocity at the mouth camera (solid black line) and Freezeout Island (dashed red line). Positive wind velocity indicates landward wind. Date ticks are centered at midnight local time and vertical gray bars indicate perched conditions and closure periods.

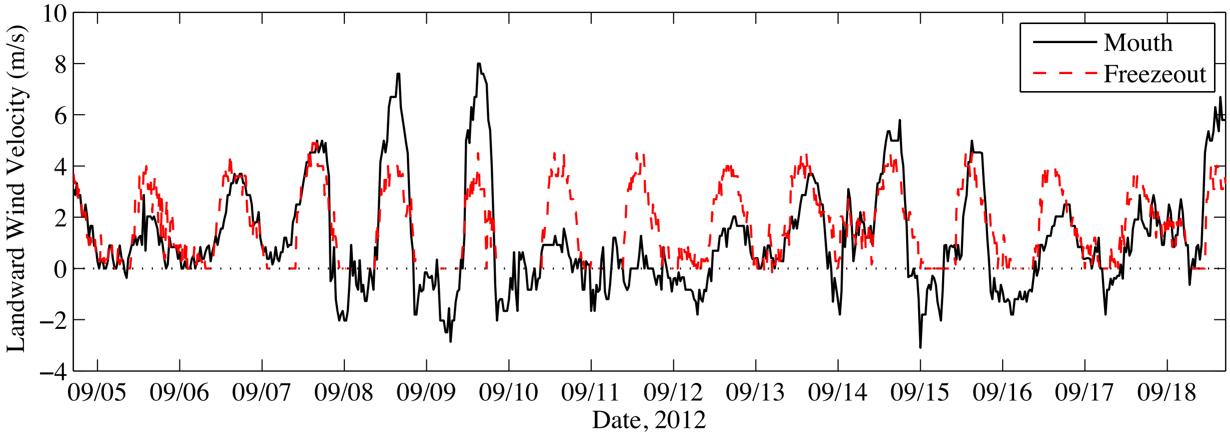

Figure 6.2 Landward component of wind velocity at the mouth camera (solid black line) and Freezeout Island (dashed red line) from 5-19 September 2012.

7. River Discharge

Measurements of Russian River discharge were obtained from the gauge operated by the U.S. Geological Survey (USGS) at Guerneville (station 11467000, waterdata.usgs.gov/nwis/). At the time of this report, these data are listed as provisional, subject to revision pending final approval. Strong diurnal oscillations of river discharge were evident during much of the month of June 2012, which may represent a period of compromised data quality.

The discharge data from the 2012 study season show relatively low flow (approximately 100 cfs) between the end of June and the middle of October. Flow increased slightly near the end of October, yet two brief closure events occurred in November when flow was approximately 300 cfs.

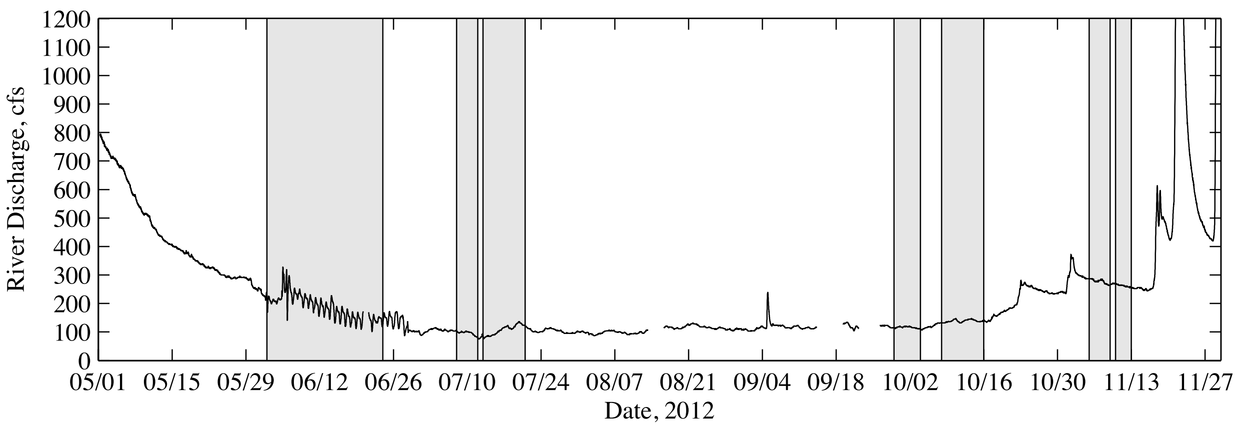

Figure 7.1 Russian River discharge measured at USGS gauge 11467000 during the 2012 study period. Vertical gray bars indicate perched conditions and closure periods.

8. Channel Current Velocities

Two Acoustic Doppler Current Profilers (ADCPs) were deployed during the 2012 study period. One was deployed at Patty's Rock and the other was placed at Heron Rookery (Figure 1.1). Both instruments were sampling from 20 June through 8 November (Table 1.1). These locations were selected because they are both in deep pools, one in the outer estuary (Patty's Rock) and one in the inner estuary (Heron Rookery). The instruments measured and recorded a velocity profile of horizontal current velocity every 10 min. with a vertical resolution of 1m. Horizontal velocities are accurate to within ±0.3% of measured current, and in the case of the Russian River Estuary, velocity was not more than 1 m/s, resulting in an overall accuracy of <0.3 cm/s.

Current velocity (magnitude and direction) data were decomposed into along and cross-stream velocity components at each ADCP location. As with wind, the dominant component for current is parallel to the channel, which is reported here as a contour of all depths (Figures 8.1 and 8.2) as well as plots of velocity near the surface and the bottom at each location (Figure 8.3).

During periods when the estuary mouth is open, tidal currents dominate flow within the estuary, with landward flow near the bottom and seaward flow near the surface, particularly at the Patty's Rock location in the outer estuary (Figures 8.1, 8.2). When the mouth is constricted, perched, and finally closed, these currents diminish significantly (Figures 8.3, 8.4). However, several flow events occurred during closures, which likely represent wind-driven circulation (Figures 8.4, 8.5).

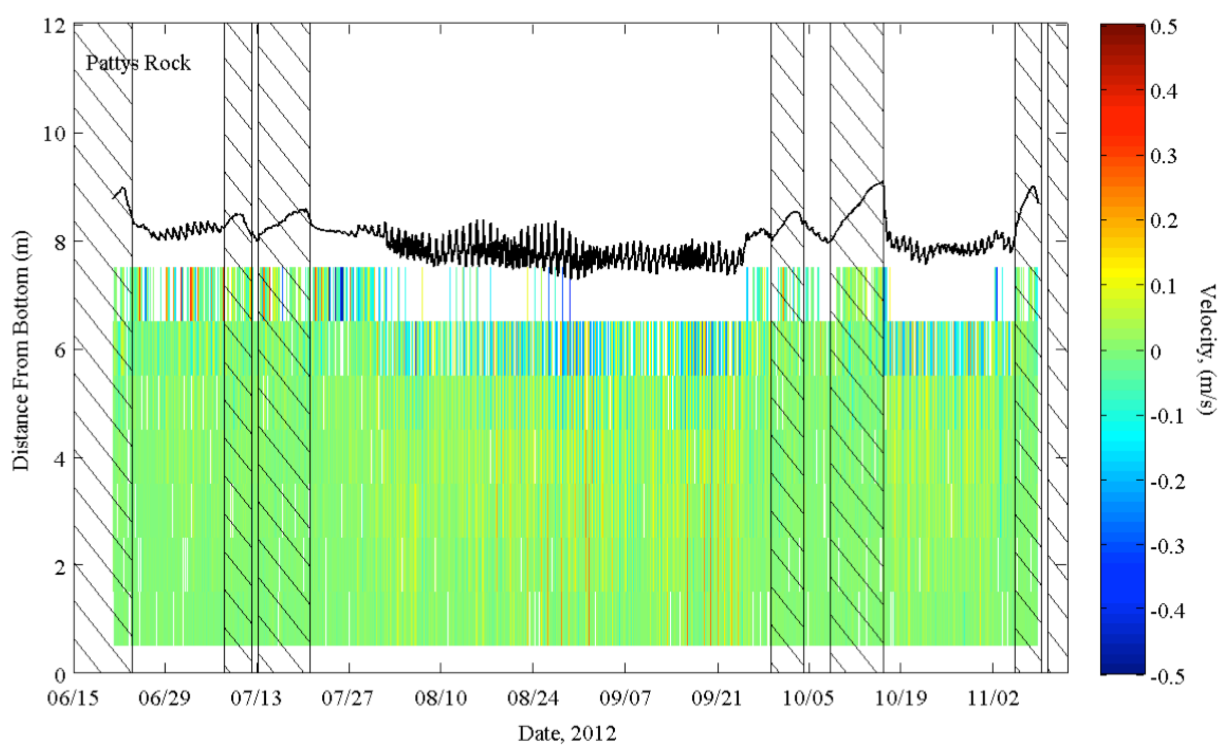

Figure 8.1 Contour plot of velocity through the water column as recorded by the Patty's Rock ADCP. The black line is the depth recorded by the ADCP and the hatched areas represent closure periods.

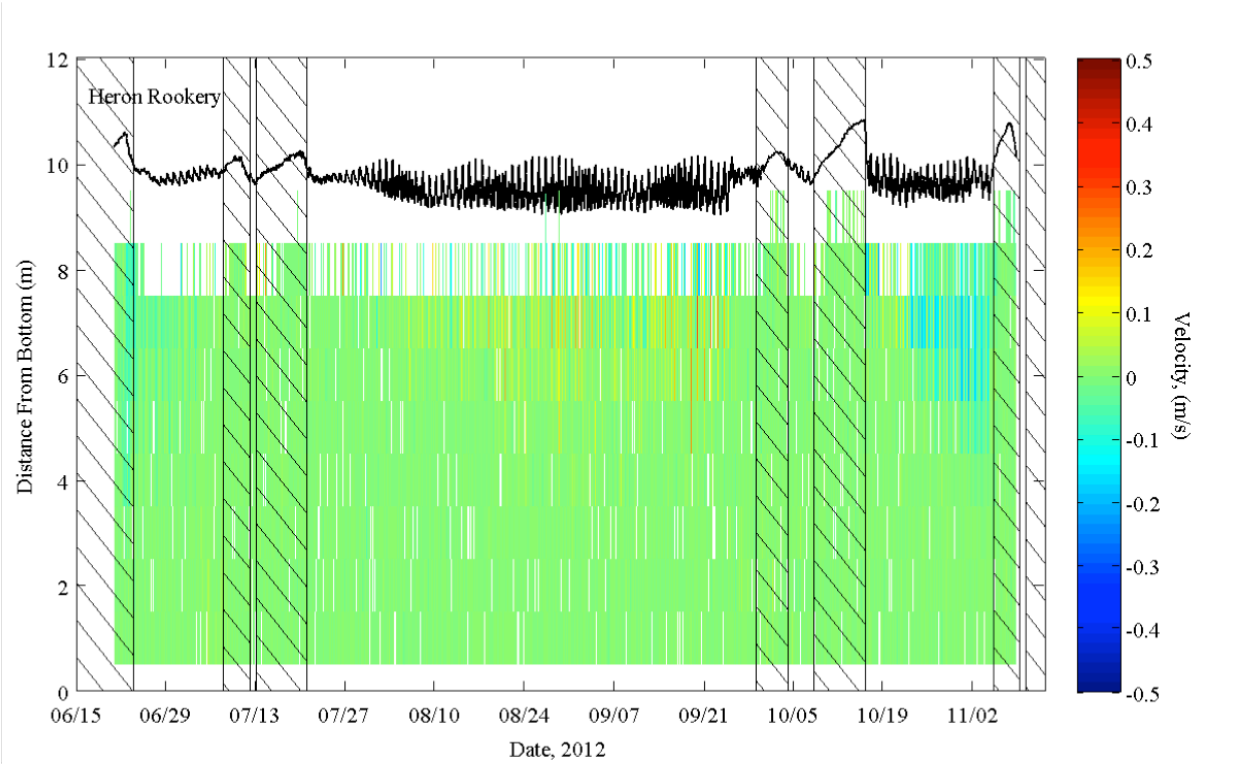

Figure 8.2 Contour plot of velocity through the water column as recorded by the Heron Rookery ADCP. The black line is the depth recorded by the ADCP and the hatched areas represent closure periods.

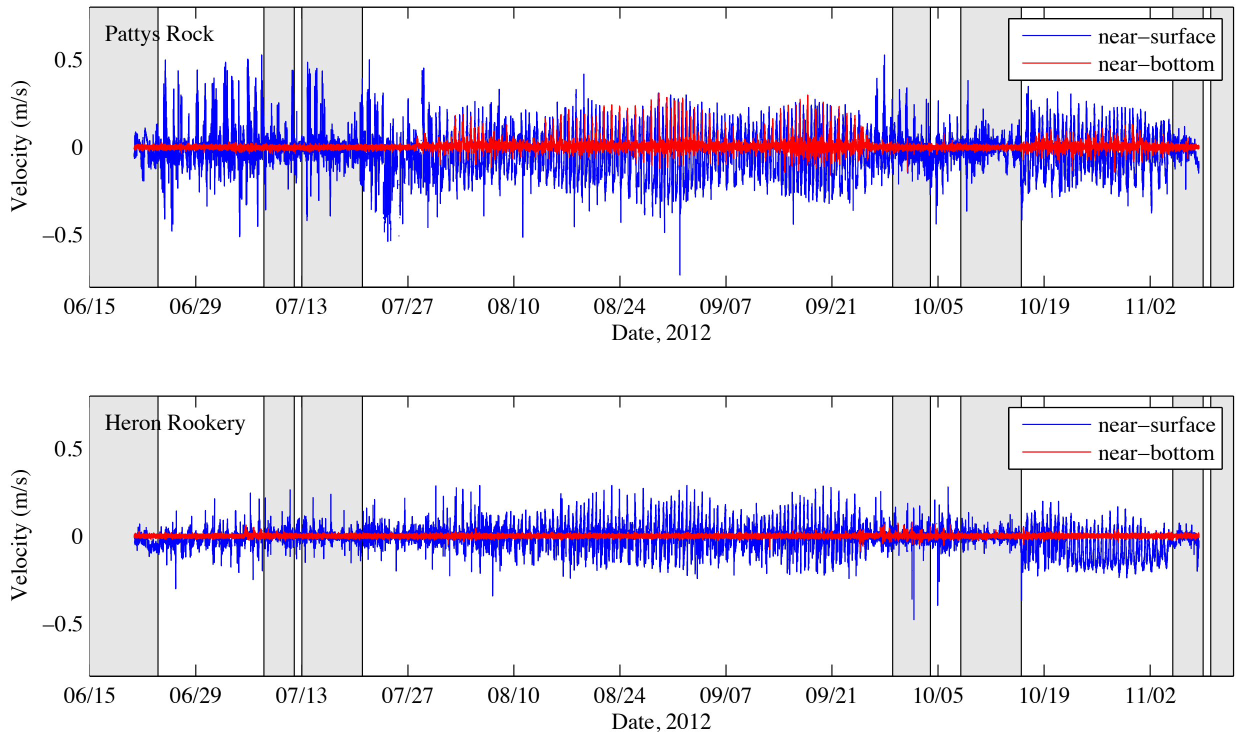

Figure 8.3 Near-surface (blue) and near-bottom (red) flow at Patty's Rock (top) and Heron Rookery (bottom) over the entire record. Negative flows are toward the mouth. Gray bars indicate perched conditions and closure periods.

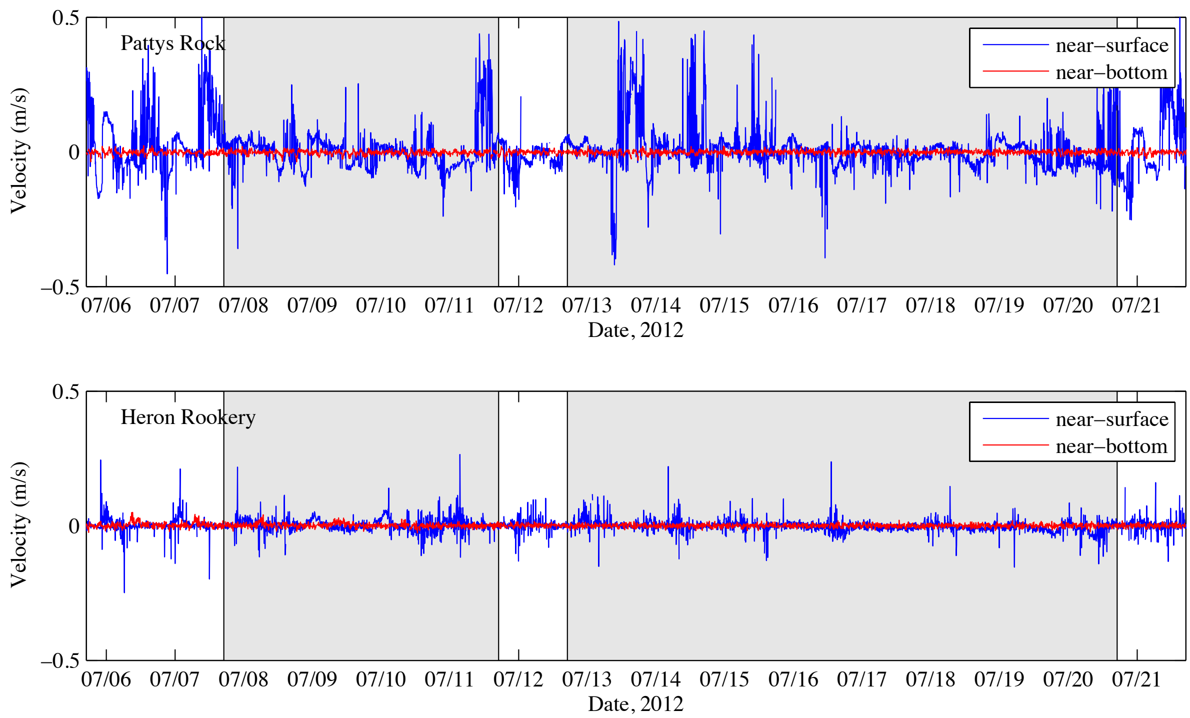

Figure 8.4 Near-surface (blue) and near-bottom (red) flow at Patty's Rock (top) and Heron Rookery (bottom) during perched conditions from 5-21 July 2012. Negative flows are toward the mouth. Gray bars indicate perched conditions.

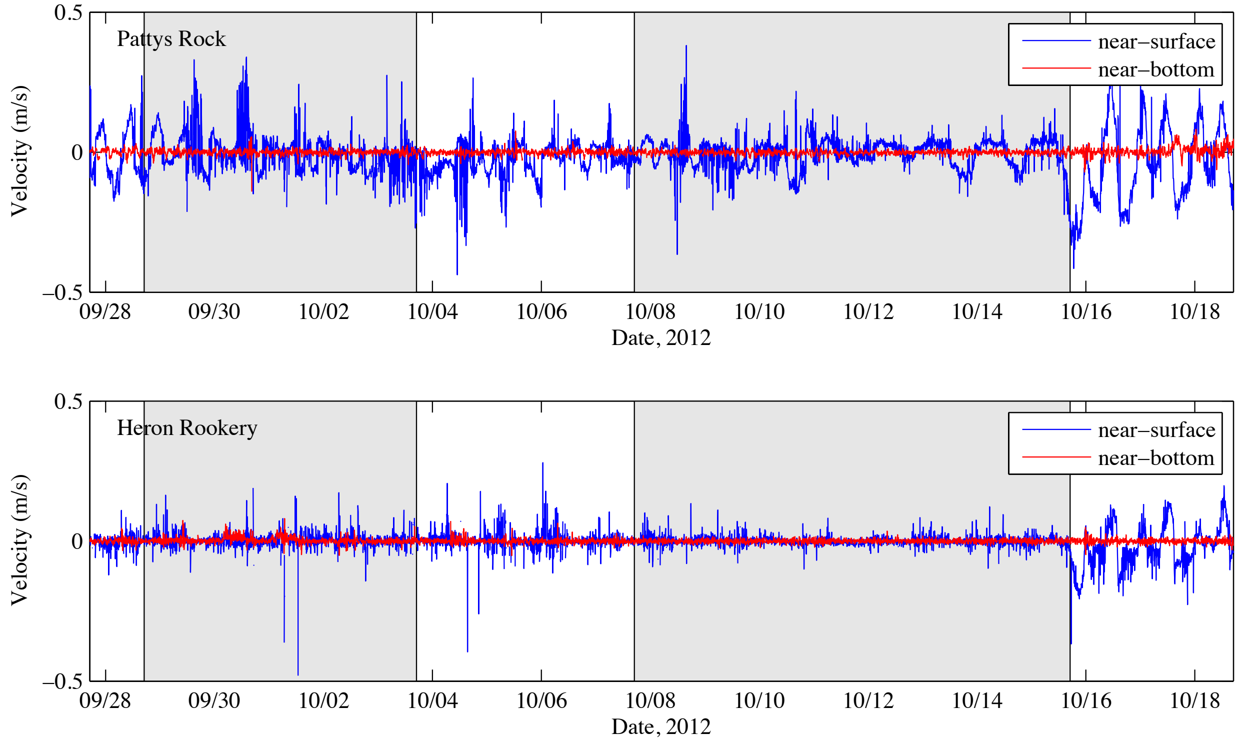

Figure 8.5 Near-surface (blue) and near-bottom (red) flow at Patty's Rock (top) and Heron Rookery (bottom) over two closure periods from 28 September through 18 October 2012. Negative flows are toward the mouth. Gray bars indicate the closure periods.

9. Moored Temperature and Salinity

Two moorings were deployed during the 2012 study season in order to record time series of temperature and salinity throughout the water column (refer to Table 1.1 for deployment dates by location). Each mooring was deployed alongside an ADCP, one at Patty's Rock and another at Heron Rookery. Each mooring had a Sea Bird Electronics Model 37SM MicroCAT at the surface and bottom to record temperature and salinity. Also, each mooring was equipped with Sea Bird Electronics Model 39 thermistors 3m, 5m, and 7m above the bottom that recorded temperature.

Salinity in the outer estuary (Patty's Rock) followed oceanic salinity closely at the bottom and was highly variable at the surface. During closure periods and perched conditions, surface salinity became very low and stable. Temperature at the surface and at depth mostly tracked the salinity patterns, with low temperature associated with high salinity. However, during closure periods and perched conditions, temperature increased monotonically, especially at depth. The greatest increases in temperature occurred near the surface during the perched conditions in July, but the warming extended all the way to the bottom. Following the perched conditions when the estuary returned to tidal conditions, cooling occurred at the shallowest depths first, gradually deepening to the bottom over several days (Figure 9.1).

Surface salinity was generally much lower in the inner estuary (Heron Rookery) than the outer estuary, and was mostly fresh except for intrusions of salt at high tides during August and September. At the bottom, salinity patterns were characterized by rapid changes followed by periods of stability. Bottom salinity increased just prior to closure events as the mouth became increasingly constricted. Temperature at the bottom increased with the rise in salinity at the beginning of July, but did not change significantly during the salinity increase in late September. The coolest temperatures were at the surface through much of the study season (Figure 9.2).

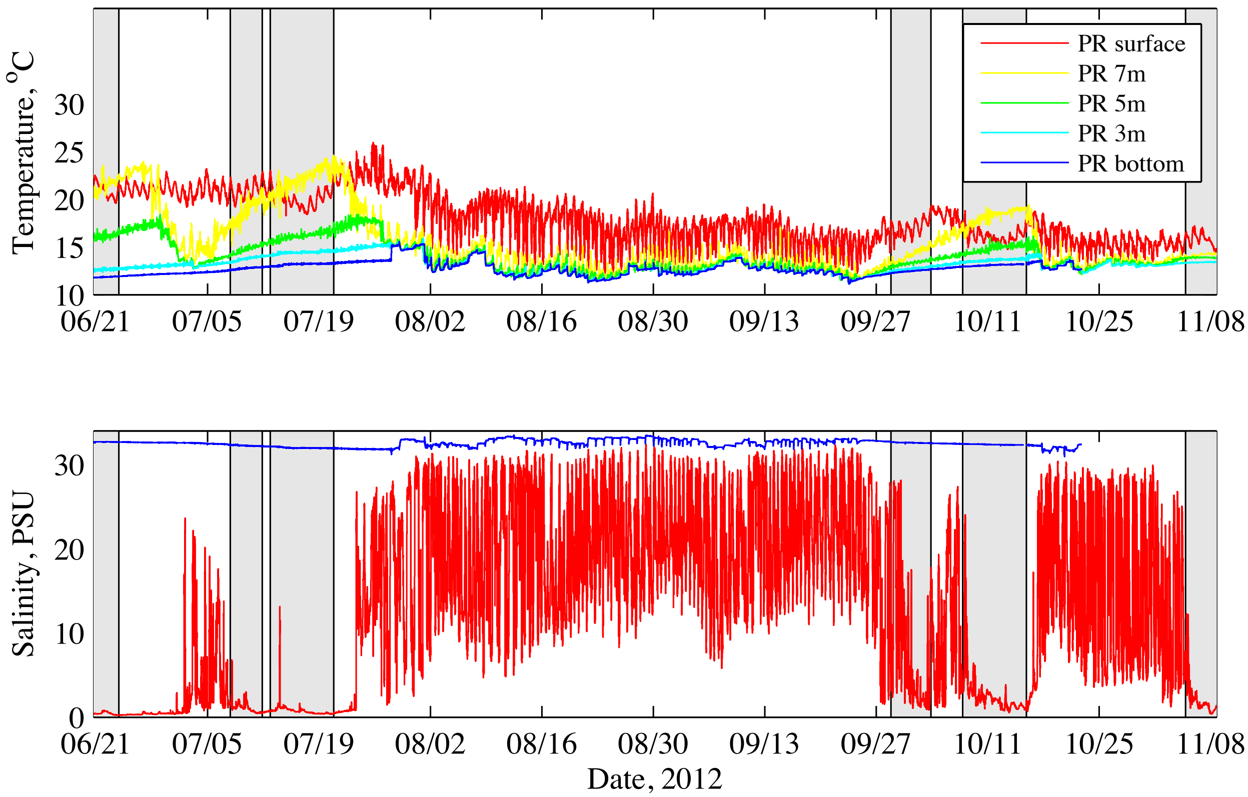

Figure 9.1 Temperature (top panel) and salinity (bottom panel) from the mooring at Patty's Rock. Temperature was recorded at multiple depths, and distances indicated in the legend are distances from the bottom of the mooring. Salinity was recorded at the bottom (blue line) and surface (red line). Gray bars indicate perched conditions and closure periods.

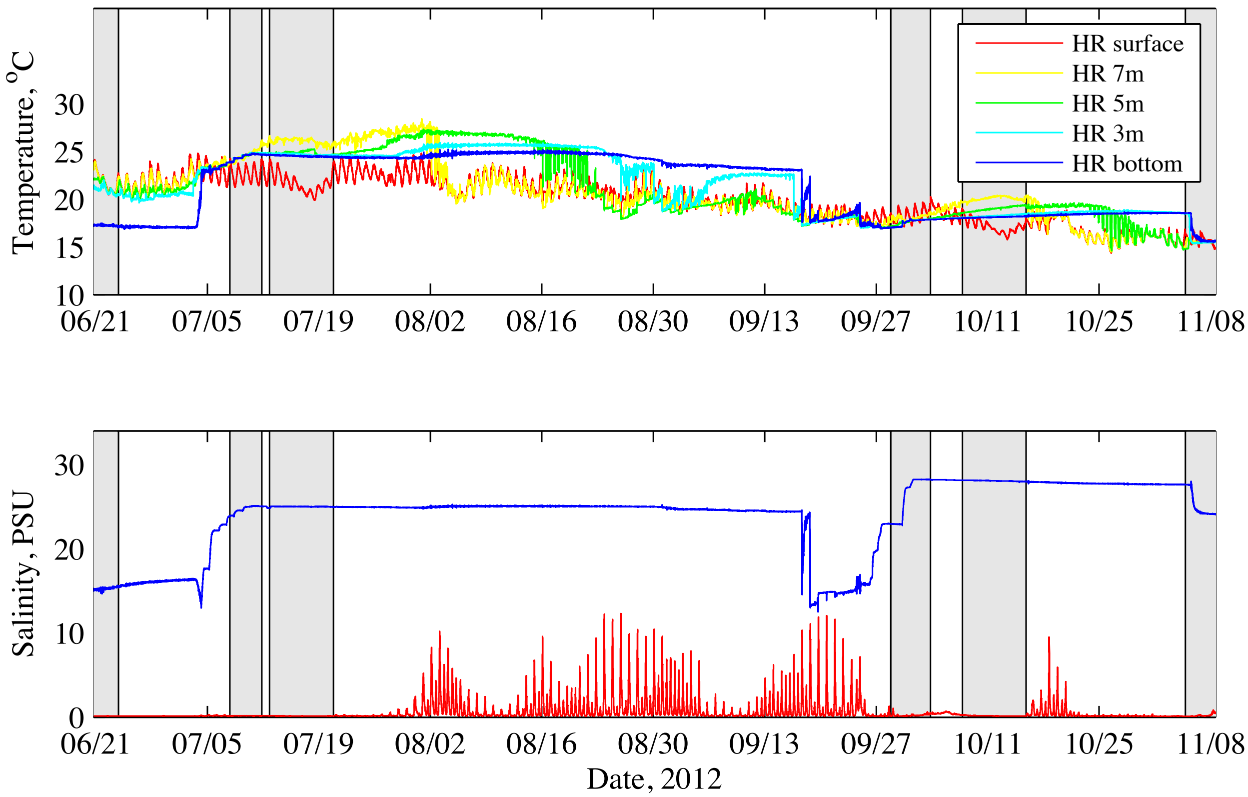

Figure 9.2 Temperature (top panel) and salinity (bottom panel) from the mooring at Heron Rookery. Temperature was recorded at multiple depths, and distances indicated in the legend are distances from the bottom of the mooring. Salinity was recorded at the bottom (blue line) and surface (red line). Gray bars indicate perched conditions and closure periods.

10. CTD Transects

Longitudinal CTD transects were conducted regularly using a small boat by making vertical profiles at 12 stations from the mouth to Moscow Bridge. Transects were conducted more often during perched conditions and closure periods, particularly near the beginning of each event. Also, sometimes low water levels or time constraints prohibited access to some sampling stations, resulting in the omission of these stations from the transect. The dates, times, parameters sampled, and stations omitted from each transect are described in Table 10.1.

In addition to the standard CTD parameters of conductivity, temperature (T), and depth (from which salinity (S) and density are derived), the profiling apparatus used to conduct these transects also included additional instruments to record dissolved oxygen (DO), fluorescence (Fl, used to calculate chlorophyll concentration), beam transmission (BT, a measure of water clarity), and photosynthetically active radiation (PAR). On any given transect during the sampling season, data from one or more of these auxiliary instruments may have been removed from the dataset due to malfunction or physical removal from the profiler (summary of parameters sampled on each date is provided in Table 10.1).

Temperature, salinity, and dissolved oxygen are direct measures of habitat suitability, while the other parameters allow for additional insights into water quality. By measuring chlorophyll in the water column we can gain a better understanding of when and where phytoplankton may be producing additional DO, which is further enhanced by including light transmission data such as PAR and BT.

Contour plots were created based on spatial interpolation between CTD cast locations, which are represented by black dots on the plots. The elevations represented in the plots are based on water surface elevation at the time of each cast, and the interpolations were truncated at the thalweg depth based on distance from the mouth. The upper limit of the contouring was based on the uppermost data available in each cast and does not necessarily represent the elevation of the surface of the water. Contour plots of all parameters from each transect are included here as Figures 10.1 through 10.32.

The first CTD transect was conducted on 30 May 2012 when the estuary mouth was beginning to become constricted for the first time of the season (Figure 1.1). The most obvious spatial pattern in water properties was vertical temperature and salinity stratification in the outer estuary with relatively warm and fresh water above cool salty water. Water in the inner estuary was comprised mainly of warm and fresh water with the exception of cool salty water in the deepest sections of Sheephouse Creek and Heron Rookery. Dissolved oxygen was relatively high throughout the water column at all stations except at in the deepest section of Heron Rookery. Chlorophyll fluorescence was low throughout the estuary with several patches of higher chlorophyll associated with the cool salty water in the outer estuary (Figure 10.1).

By 3 June 2012, conditions at the estuary mouth had become perched and water surface elevation within the estuary had begun to rise but still showed a weak tidal signal (Figure 1.1). The data collected during this transect showed similar patterns to those seen during the previous transect, but chlorophyll fluorescence was significantly higher in the cool salty water in the outer estuary than before. This chlorophyll increase was also associated with increased levels of DO (Figure 10.2).

The 8 June 2012 transect was conducted when the mouth was still perched (Figure 1.1). The data were remarkably similar to the previous transect but the patch of high chlorophyll had intensified further and was associated with additional increases in DO (Figure 10.3).

By 10 June 2012, the estuary mouth had become mostly closed with a very small outflow channel (Figures 1.1, 4.1). At this point, the high chlorophyll patch had moved seaward and was deeper than before. Dissolved oxygen had increased in the inner estuary while decreasing in the outer estuary (Figure 10.4). These patterns continued the following day, with DO decreasing further in the outer estuary but remaining relatively high in the inner estuary (Figure 10.5).

On 12 June 2012, the mouth remained nearly closed (Figure 1.1). The patch of high chlorophyll was mostly dispersed, with isolated patches remaining at depth in the outer estuary. DO was depleted in the deeper sections of both the inner and outer estuary (Figure 10.6).

Water surface elevation had increased further by 13 June 2012 (Figure 1.1), and the CTD transect data shows an increase in the thickness of the surface freshwater layer. Chlorophyll remained high only in the deepest sections of the outer estuary, and DO was very low in deep sections of both the outer and inner estuary (Figure 10.7).

The channel at the estuary mouth widened slightly and water surface elevation dropped by approximately 0.5m preceding the transect on 15 June 2013 (Figure 1.1). This appeared to have little effect on conditions within the estuary, with the exception that the surface layer of freshwater was less thick. No notable changes were observed in temperature, chlorophyll, or DO (Figure 10.8).

The next CTD transect was completed on 9 July 2012 following a period of approximately two weeks when the mouth was constricted and conditions were weakly tidal (Figure 1.1). By this time, temperature was warmest in the inner estuary and cooler in the outer estuary, especially at depth. High salinity water was present well into the inner estuary, capped by a layer of freshwater approximately 1m thick throughout the estuary. DO levels were moderately high throughout the estuary, and patches of high chlorophyll water were present in deeper water very near the mouth as well as at Osprey Rookery and Heron Rookery (Figure 10.9).

On 26 July 2012, the mouth was widening and was in the process of returning to a tidal channel (Figure 1.1). Temperature had warmed considerably at depth in the inner estuary during the previous weeks of weak tides and stratified conditions. Also, a large subsurface patch of high chlorophyll water was observed near the upper bound of the salt layer throughout the estuary (Figure 10.10).

One week later on 1 August 2012, the mouth had continued to widen but the tidal range was still slightly constricted (Figure 1.1). The warm temperatures seen in the inner estuary had cooled everywhere except at Heron Rookery where subsurface temperature remained above 25^{o}C. High levels of subsurface chlorophyll were observed only in the inner estuary (Figure 10.11).

On 8 August 2012, conditions at the mouth were almost fully tidal (Figure 1.1). The warm salty water at Heron Rookery had deepened but was still present. The high chlorophyll water below the surface in the inner estuary extended farther seaward but its vertical extent had narrowed to a thin band (Figure 10.12).

Tidal conditions prevailed for approximately the next six weeks (Figure 1.1), and the transects completed between 15 August and 25 September 2012 show gradual deepening of the warm, salty, low DO layer at Heron Rookery (Figures 10.13, 10.14, 10.15, 10.16, 10.17, 10.18, 10.19, 10.20). These plots also show pulses of high chlorophyll generally associated with the upper levels of the saltwater layer. DO during this period was relatively high throughout the estuary with the exception of the deep section of Heron Rookery (Figures 10.18, 10.19, 10.20).

The estuary mouth became constricted once again on 25 September 2012 resulting in weakened tidal fluctuations within the estuary (Figure 1.1). On 27 September 2012 cold salty water extended into the inner estuary to Osprey Rookery. DO was higher at Heron Rookery than was seen in previous transects. There was a subsurface patch of high chlorophyll water in much of the outer estuary that extended to Sheephouse Creek and was associated with high DO levels (Figure 10.21).

On 1 October 2012, the channel at the estuary mouth was closed and water surface elevation had begun to increase (Figure 1.1). High salinity water was found at Heron Rookery and some salt was observed at Freezeout Island as well. DO levels were high through much of the estuary, including at the bottom at Heron Rookery, but some drawdown was seen in the deeper pools of the outer estuary. Chlorophyll levels were relatively low with a thin band of higher chlorophyll at the top of the saltwater layer at Sheephouse Creek and Osprey Rookery (Figure 10.22).

On 2 October 2012, the mouth remained closed and water surface elevation had increased further (Figure 1.1). Saltwater had been pushed farther into the estuary, and significant stratification was seen at Freezeout Island. DO levels remained high throughout the estuary except levels in the deep pools of the outer estuary were even lower than the previous day. A band of high chlorophyll water was present at the upper extent of the saltwater layer in the outer estuary (Figure 10.23).

The estuary mouth was still closed on 3 October 2012 (Figure 1.1). Temperature, salinity, and DO patterns were very similar to those seen on the previous day, but chlorophyll levels were low throughout the estuary (Figure 10.24).

By 5 October 2012 the estuary mouth had opened allowing weak tidal flow and a slight decrease in water surface elevation (Figure 1.1). However, conditions within the estuary remained quite similar to those seen on 3 October, except there was less saltwater at Freezeout Island. DO drawdown continued in the outer estuary and at Freezeout Island (Figure 10.25).

Weak tidal conditions had continued preceding the transect on 7 October 2012 (Figure 1.1). Temperature, salinity, and DO patterns were very similar to those seen on the previous transect, but small patches of high chlorophyll water were seen at various depths throughout the estuary (Figure 10.26).

The estuary mouth closed again on 8 October 2012 resulting in increasing water surface elevation within the estuary (Figure 1.1). By 12 October 2012, the surface layer of freshwater had increased in thickness compared with the previous transect. Warmer temperatures were seen in the upper levels of the saltwater layer throughout the estuary, which was also associated with high levels of chlorophyll and elevated DO. In all deep pools with salinity stratification, DO levels were very low, particularly in the outer estuary (Figure 10.27).

The estuary mouth remained closed on 15 October 2012 and water surface elevation had increased further (Figure 1.1). The surface freshwater layer was even thicker than before, below which slight additional warming had occurred. DO remained near zero in the deep pools and was elevated near the upper extent of the saltwater layer throughout the estuary, associated with high chlorophyll levels (Figure 10.28).

The estuary mouth self-breached just following the transect on 15 October 2012, and by the following day water surface elevation had decreased (Figure 1.1). The thickness of the freshwater layer decreased slightly but the depth of the top of the saltwater layer also deepened. DO remained low at depth throughout the estuary, and chlorophyll levels dropped (Figure 10.29).

In the days following the breach, tides became gradually more pronounced within the estuary as the channel continued to open (Figure 1.1). On 18 October 2012, the outer estuary was characterized by cool, saline, and oxygen rich water with very low chlorophyll levels. DO remained low in the middle to inner estuary and a patch of subsurface chlorophyll was present in the inner estuary (Figure 10.30).

Tides had returned to nearly their full range by 20 October 2012 (Figure 1.1). Cool, saline water was found in the outer estuary and stratified conditions were present in the inner estuary. DO levels were relatively high throughout most of the estuary except the deepest sections in the outer estuary and at Sheephouse Creek and Heron Rookery. Chlorophyll levels were very low throughout the estuary (Figure 10.31).

Tidal conditions persisted through 22 October 2012 (Figure 1.1). Temperature and salinity retained a similar pattern to the previous transect, with cool salty water in the outer estuary and slightly warmer fresh water comprising much of the inner estuary. DO levels were relatively high everywhere except Sheephouse Creek and Heron Rookery, and chlorophyll levels remained low (Figure 10.32).

Table 10.1 CTD transect dates, times, parameters sampled, and stations omitted from the survey. Parameters sampled included temperature (T), salinity (S), dissolved oxygen (DO), fluorescence (Fl), beam transmission (BT), and photosynthetically active radiation (PAR). Stations included Mouth (MO), Penny Island (PI), Patty's Rock (PR), Bridgehaven (BH), Willow Creek (WC), Flats (FL), Sheephouse Creek (SC), Osprey Rookery (OR), Heron Rookery (HR), Freezeout Island (FI), Freezeout Creek (FC), and Moscow Bridge (MB).

CTD Transects			Parameters Sampled						
Date	**Start (local)**	**End (local)**	**T**	**S**	**DO**	**Fl**	**BT**	**PAR**	**stations omitted**
30-May-2012	10:09	11:49	•	•	•	•	•	•	
3-Jun-2012	11:17	12:34	•	•	•	•	•	•	
8-Jun-2012	09:44	11:11	•	•	•	•	•	•	
10-Jun-2012	10:11	11:46	•	•	•	•	•	•	
11-Jun-2012	07:37	09:19	•	•	•	•	•	•	
12-Jun-2012	07:32	08:55	•	•	•	•	•	•	
13-Jun-2012	07:00	08:39	•	•	•	•	•	•	
15-Jun-2012	07:09	08:35	•	•	•	•	•	•	
9-Jul-2012	09:55	11:39	•	•	•	•	•	•	
26-Jul-2012	11:43	14:52	•	•		•	•	•	
1-Aug-2012	08:18	10:15	•	•		•	•	•	MB
8-Aug-2012	09:27	12:07	•	•		•	•	•	MB
15-Aug-2012	09:28	11:59	•	•		•	•	•	
23-Aug-2012	09:38	12:15	•	•		•	•	•	FC, MB
28-Aug-2012 "A"	06:31	07:31	•	•		•	•	•	MO, PI, BH, FL, FI, FC, MB
28-Aug-2012 "B"	20:38	21:38	•	•		•	•	•	MO, PI, BH, FL, FI, FC, MB
29-Aug-2012	06:34	08:17	•	•		•	•	•	FI, FC, MB
13-Sep-2012	08:05	12:04	•	•	•	•	•		
19-Sep-2012	10:36	12:45	•	•	•	•	•		
25-Sep-2012	12:45	15:01	•	•	•	•	•		
27-Sep-2012	07:58	10:18	•	•	•	•	•		
1-Oct-2012	10:58	12:41	•	•	•	•	•		
2-Oct-2012	07:38	10:01	•	•	•	•	•		
3-Oct-2012	10:41	12:11	•	•	•	•	•		
5-Oct-2012	09:53	11:18	•	•	•	•	•		
7-Oct-2012	07:24	08:47	•	•	•	•	•		
12-Oct-2012	10:46	12:59	•	•	•	•	•		
15-Oct-2012	10:50	12:30	•	•	•	•	•		
16-Oct-2012	07:39	09:44	•	•	•	•	•		
18-Oct-2012	09:00	10:31	•	•	•	•	•		FC, MB
20-Oct-2012	10:04	10:57	•	•	•	•	•		FI, FC, MB
22-Oct-2012	09:22	10:48	•	•	•	•	•		

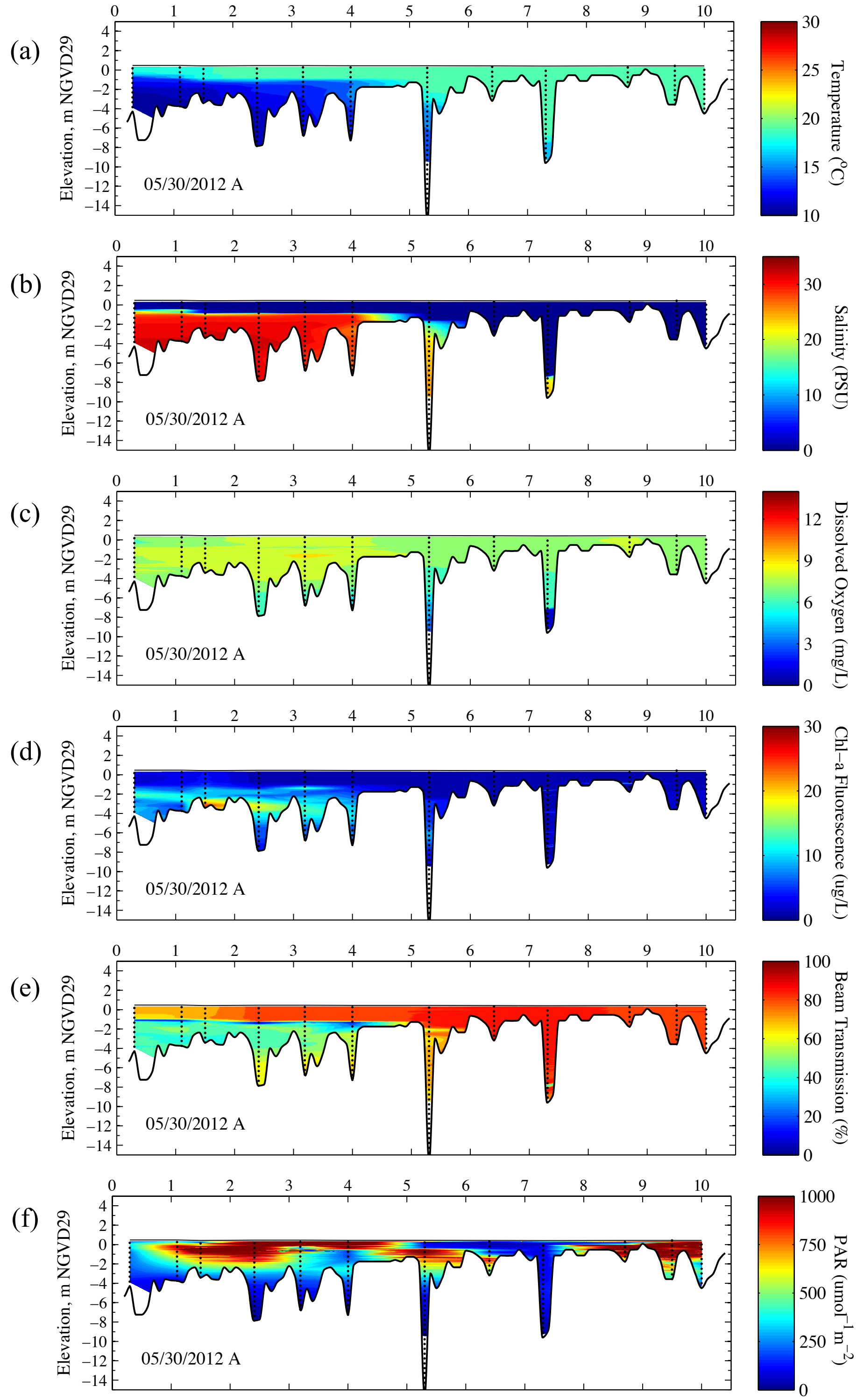

Figure 10.1 Contours of temperature (a), salinity (b), dissolved oxygen (c), chlorophyll fluorescence (d), beam transmission (e), and PAR (f) collected on 30 May 2012, when the mouth was beginning to become constricted. The x-axis represents distance (in km) from the estuary mouth.

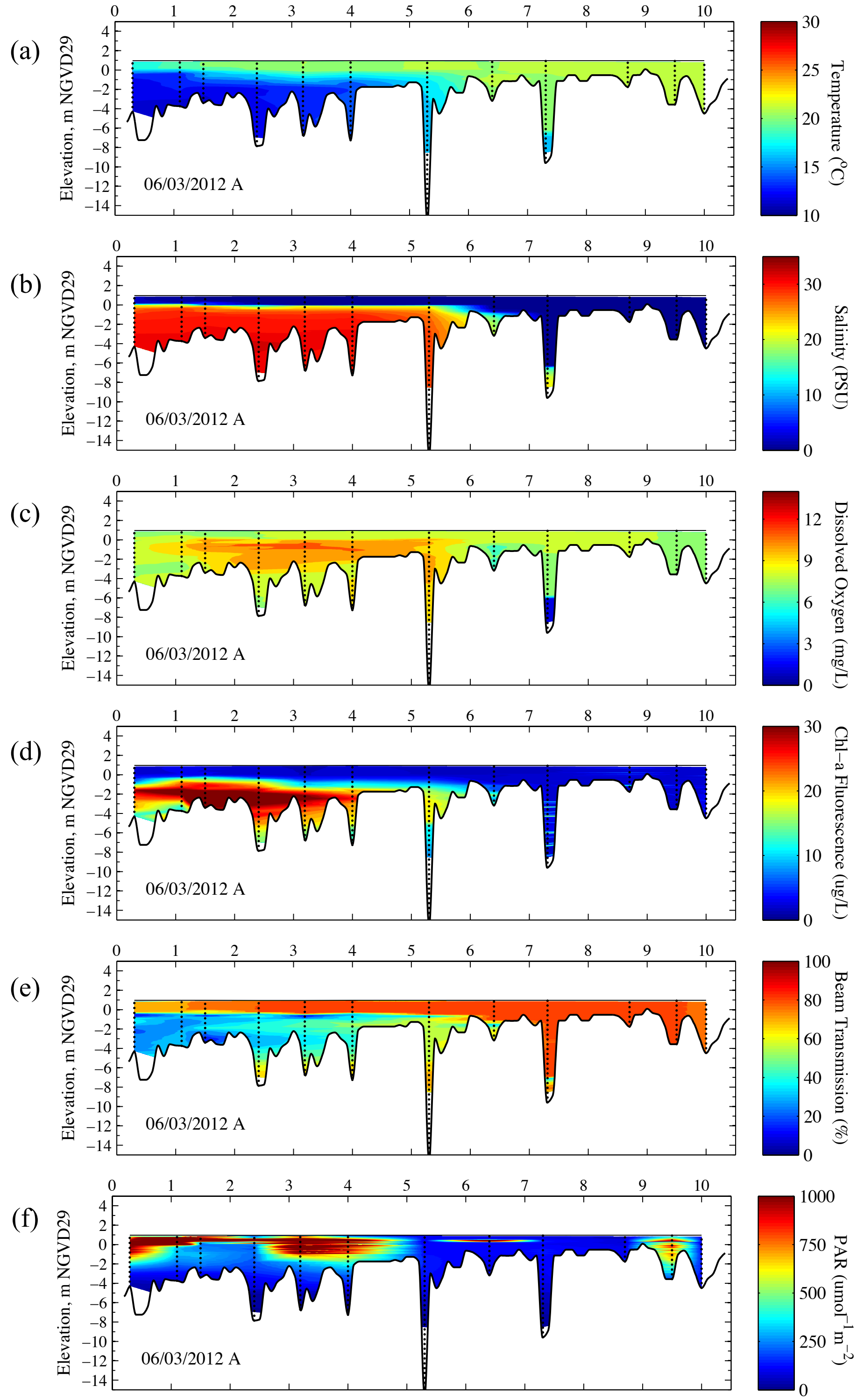

Figure 10.2 Contours of temperature (a), salinity (b), dissolved oxygen (c), chlorophyll fluorescence (d), beam transmission (e), and PAR (f) collected on 3 June 2012, when the estuary mouth was perched. The x-axis represents distance (in km) from the estuary mouth.

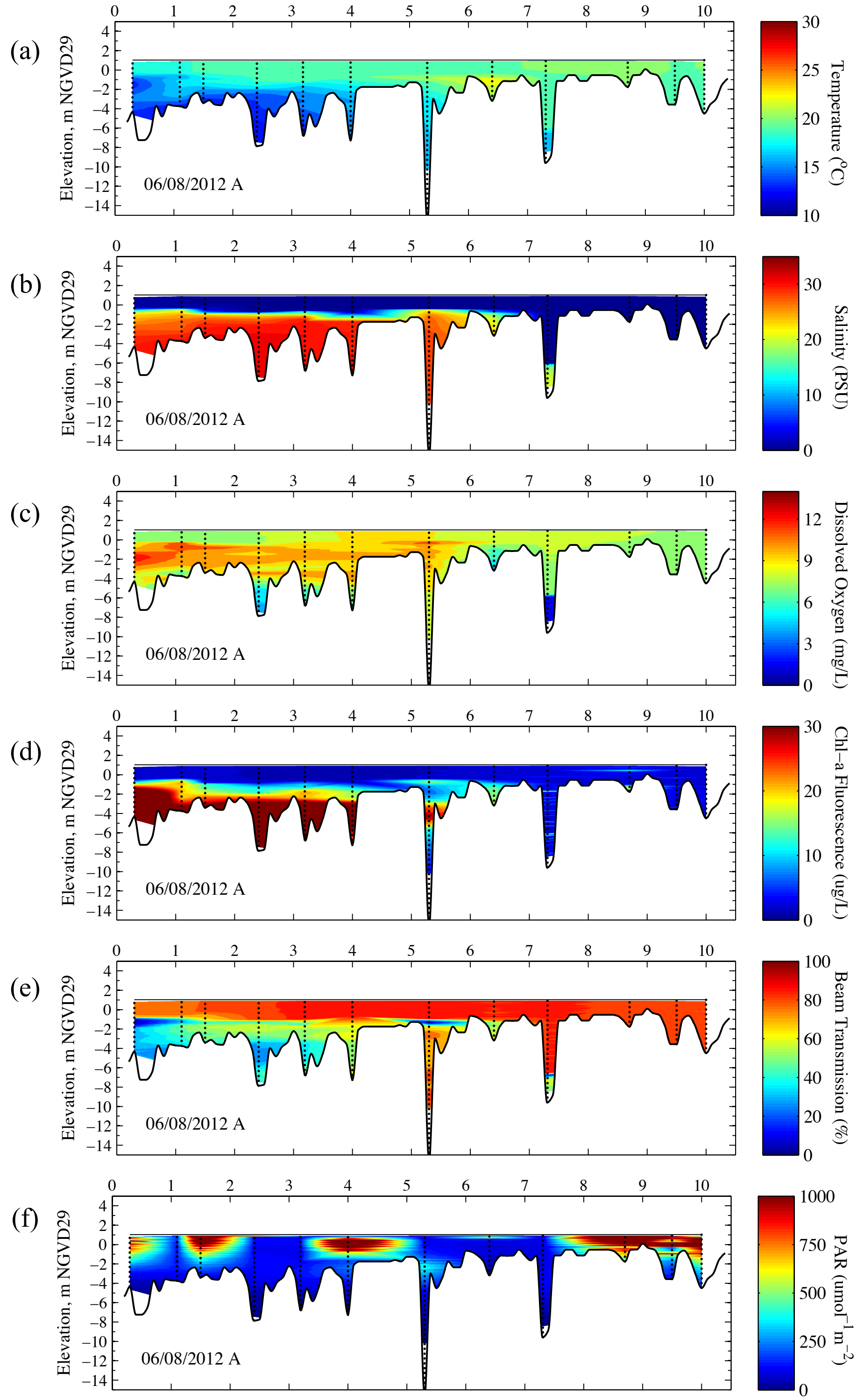

Figure 10.3 Contours of temperature (a), salinity (b), dissolved oxygen (c), chlorophyll fluorescence (d), beam transmission (e), and PAR (f) collected on 8 June 2012, when the estuary mouth had been perched for approximately 6 days. The x-axis represents distance (in km) from the estuary mouth.

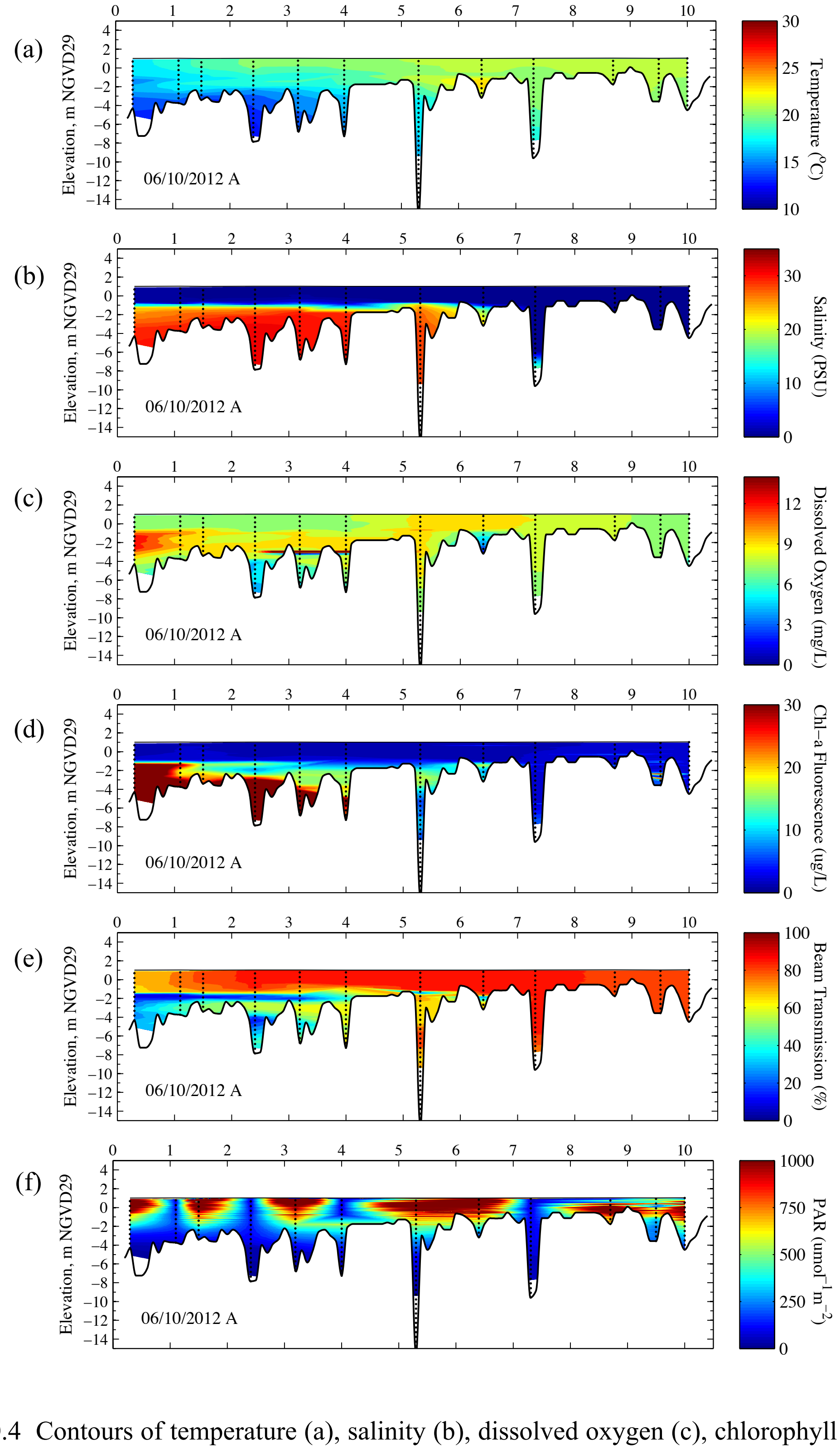

Figure 10.4 Contours of temperature (a), salinity (b), dissolved oxygen (c), chlorophyll fluorescence (d), beam transmission (e), and PAR (f) collected on 10 June 2012, when the estuary mouth had been perched for approximately 8 days. The x-axis represents distance (in km) from the estuary mouth.

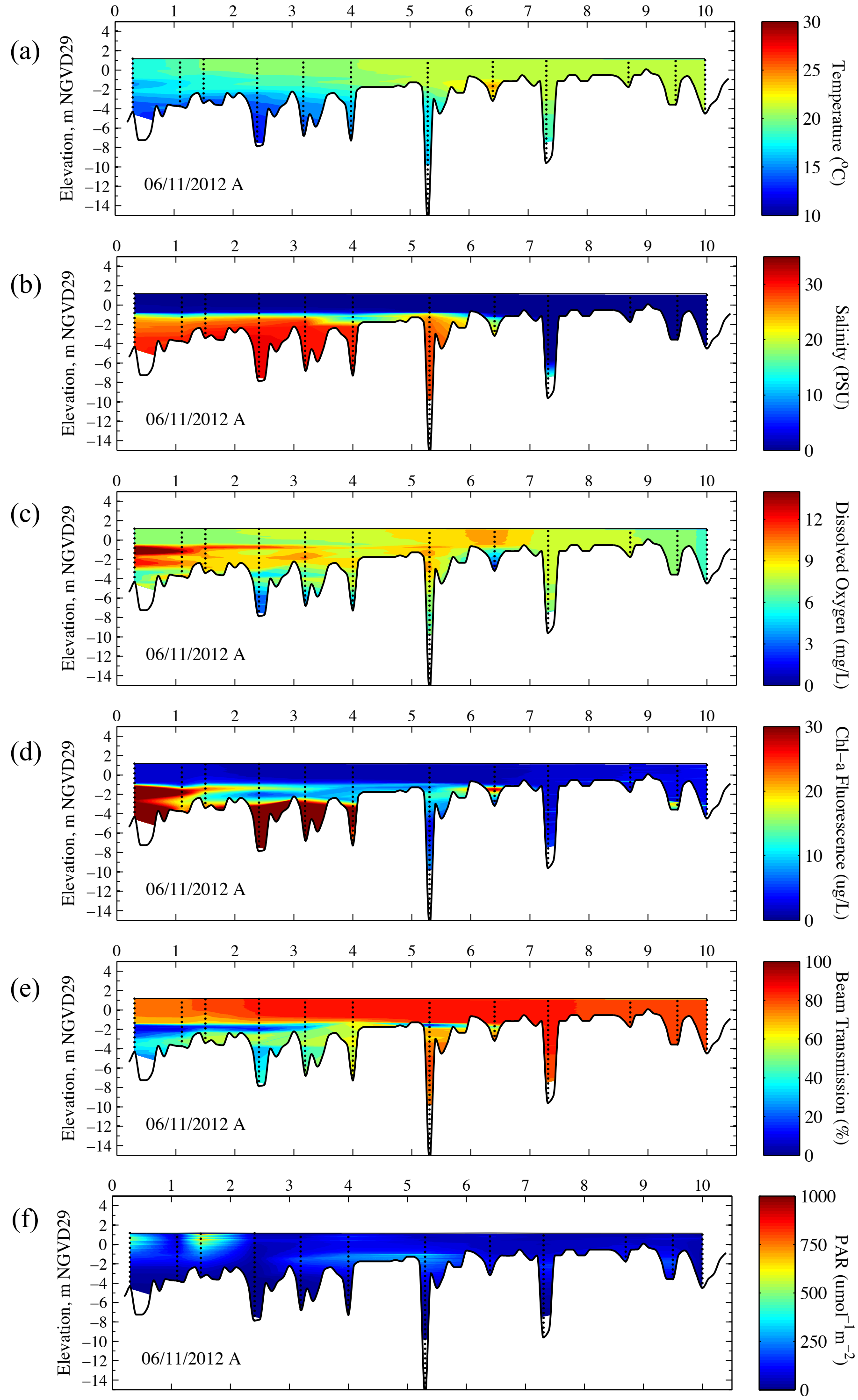

Figure 10.5 Contours of temperature (a), salinity (b), dissolved oxygen (c), chlorophyll fluorescence (d), beam transmission (e), and PAR (f) collected on 11 June 2012, when the estuary mouth had been perched for approximately 9 days. The x-axis represents distance (in km) from the estuary mouth.

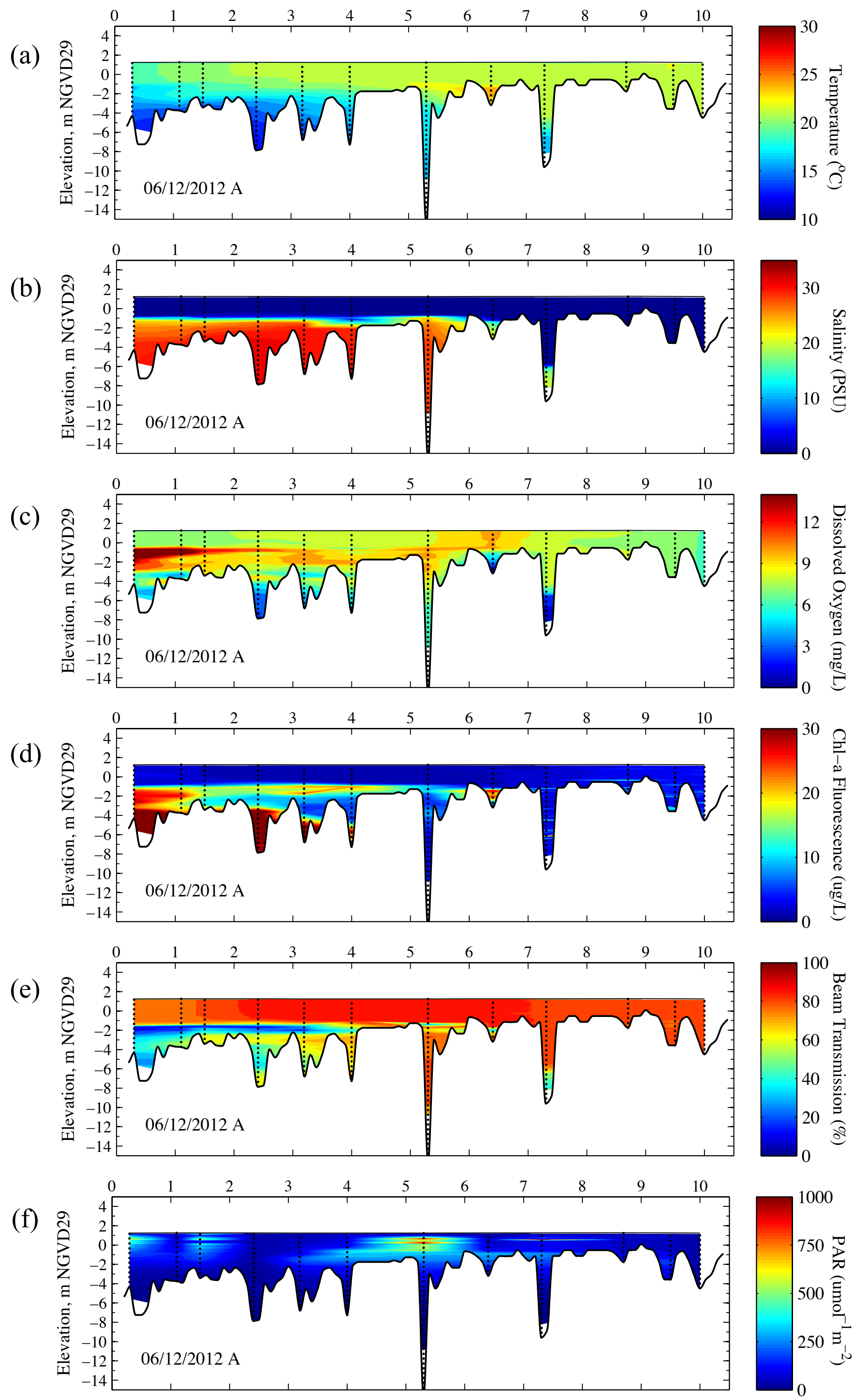

Figure 10.6 Contours of temperature (a), salinity (b), dissolved oxygen (c), chlorophyll fluorescence (d), beam transmission (e), and PAR (f) collected on 12 June 2012, when the estuary mouth had been perched for approximately 10 days. The x-axis represents distance (in km) from the estuary mouth.

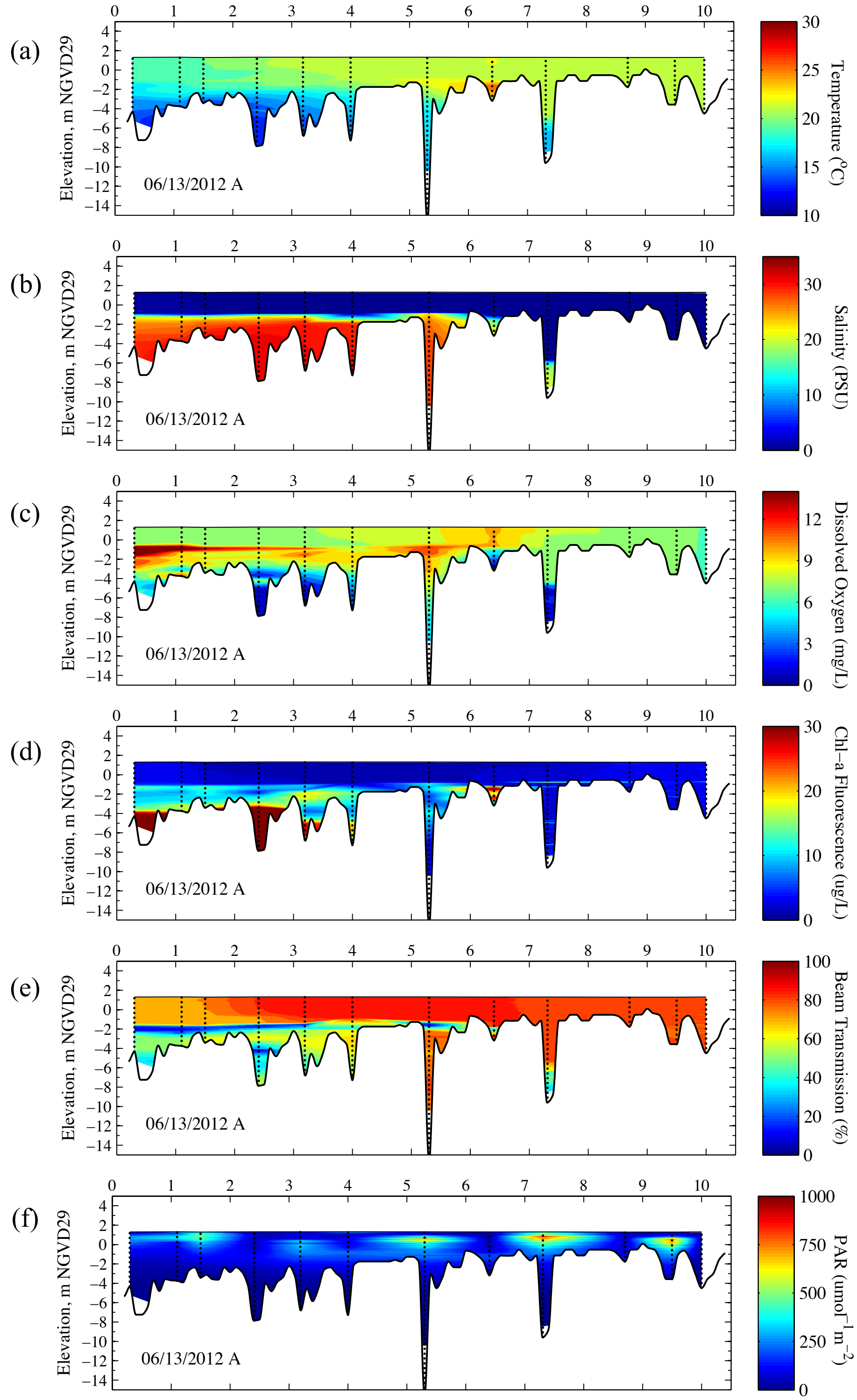

Figure 10.7 Contours of temperature (a), salinity (b), dissolved oxygen (c), chlorophyll fluorescence (d), beam transmission (e), and PAR (f) collected on 13 June 2012, when the estuary mouth had been perched for approximately 11 days. The x-axis represents distance (in km) from the estuary mouth.

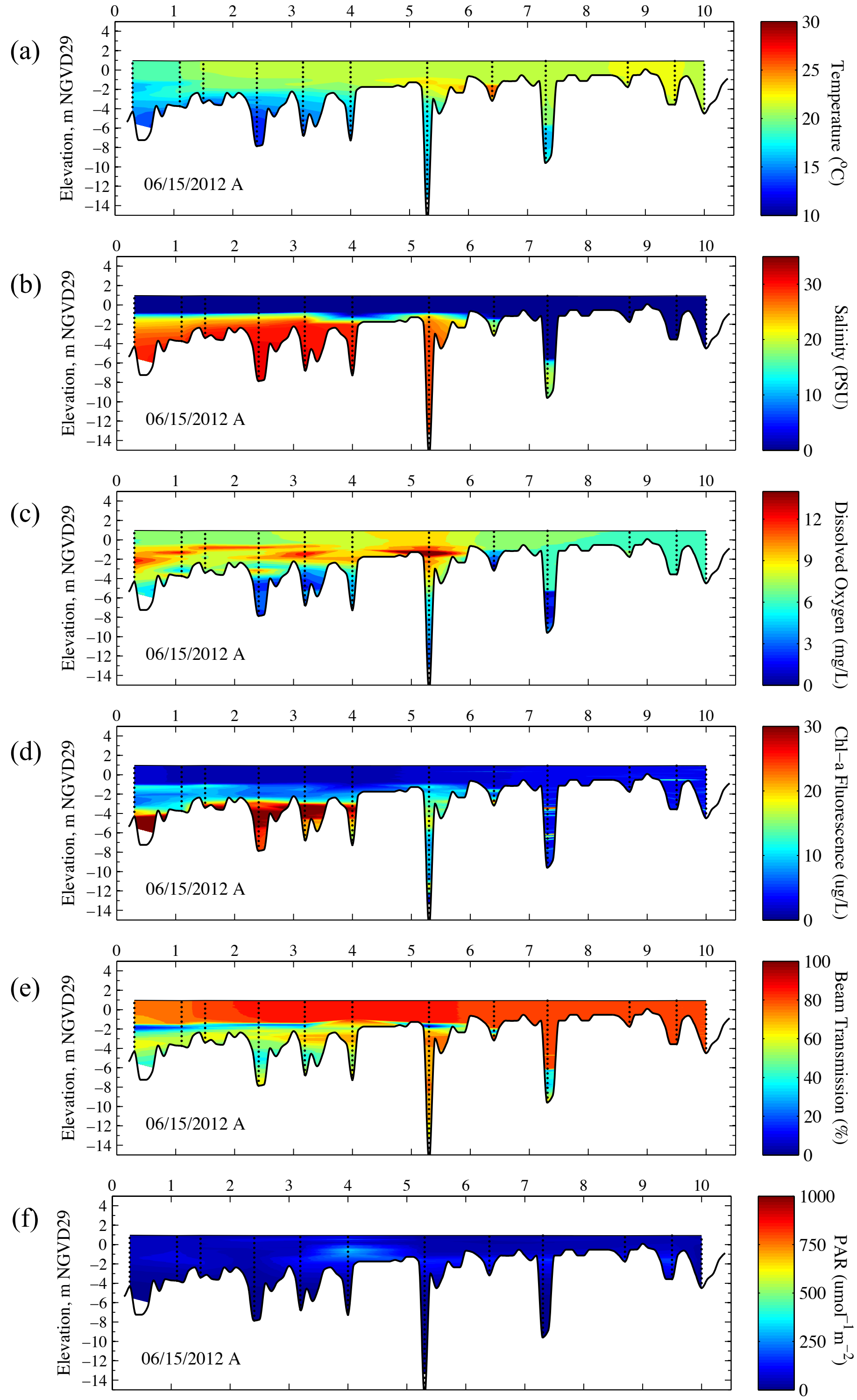

Figure 10.8 Contours of temperature (a), salinity (b), dissolved oxygen (c), chlorophyll fluorescence (d), beam transmission (e), and PAR (f) collected on 15 June 2012, when the estuary mouth had been perched for approximately 13 days but the channel was widening and deepening by this point. The x-axis represents distance (in km) from the estuary mouth.

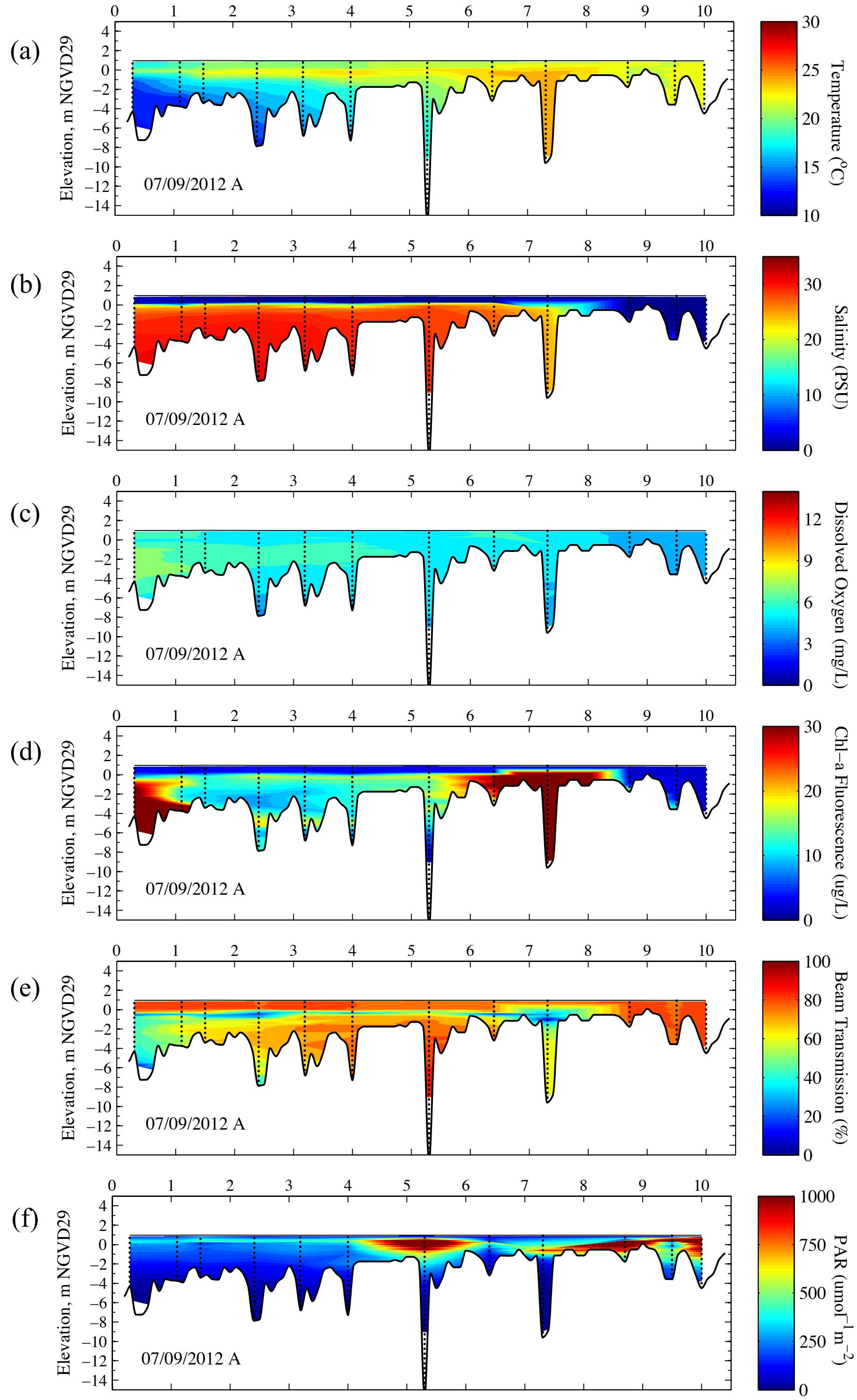

Figure 10.9 Contours of temperature (a), salinity (b), dissolved oxygen (c), chlorophyll fluorescence (d), beam transmission (e), and PAR (f) collected on 9 July 2012, after approximately 14 days of weakly tidal conditions. The x-axis represents distance (in km) from the estuary mouth.

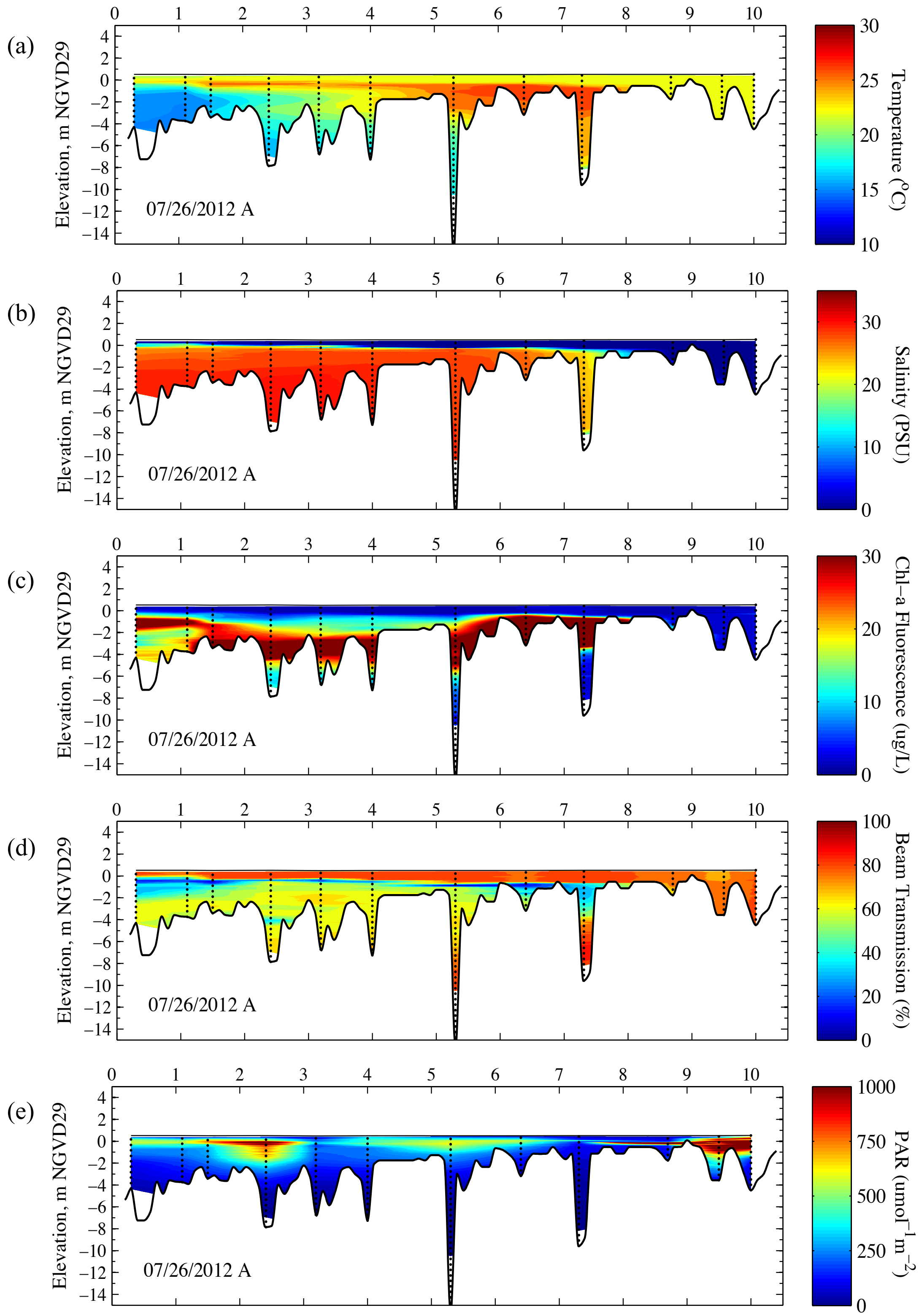

Figure 10.10 Contours of temperature (a), salinity (b), chlorophyll fluorescence (c), beam transmission (d), and PAR (e) collected on 26 July 2012, when conditions at the mouth were tidal. The x-axis represents distance (in km) from the estuary mouth.

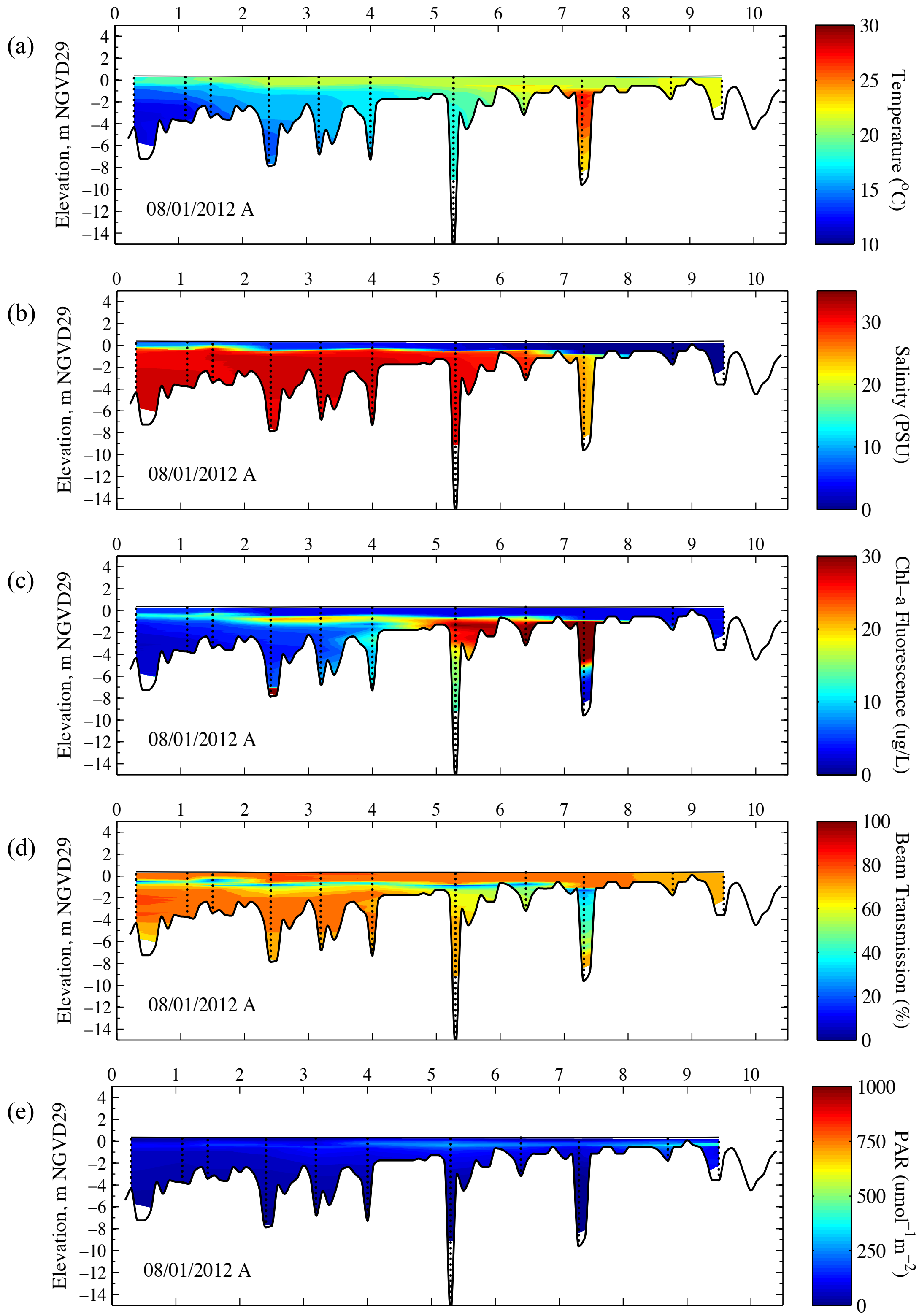

Figure 10.11 Contours of temperature (a), salinity (b), chlorophyll fluorescence (c), beam transmission (d), and PAR (e) collected on 1 August 2012, when conditions at the estuary mouth were tidal. The x-axis represents distance (in km) from the estuary mouth.

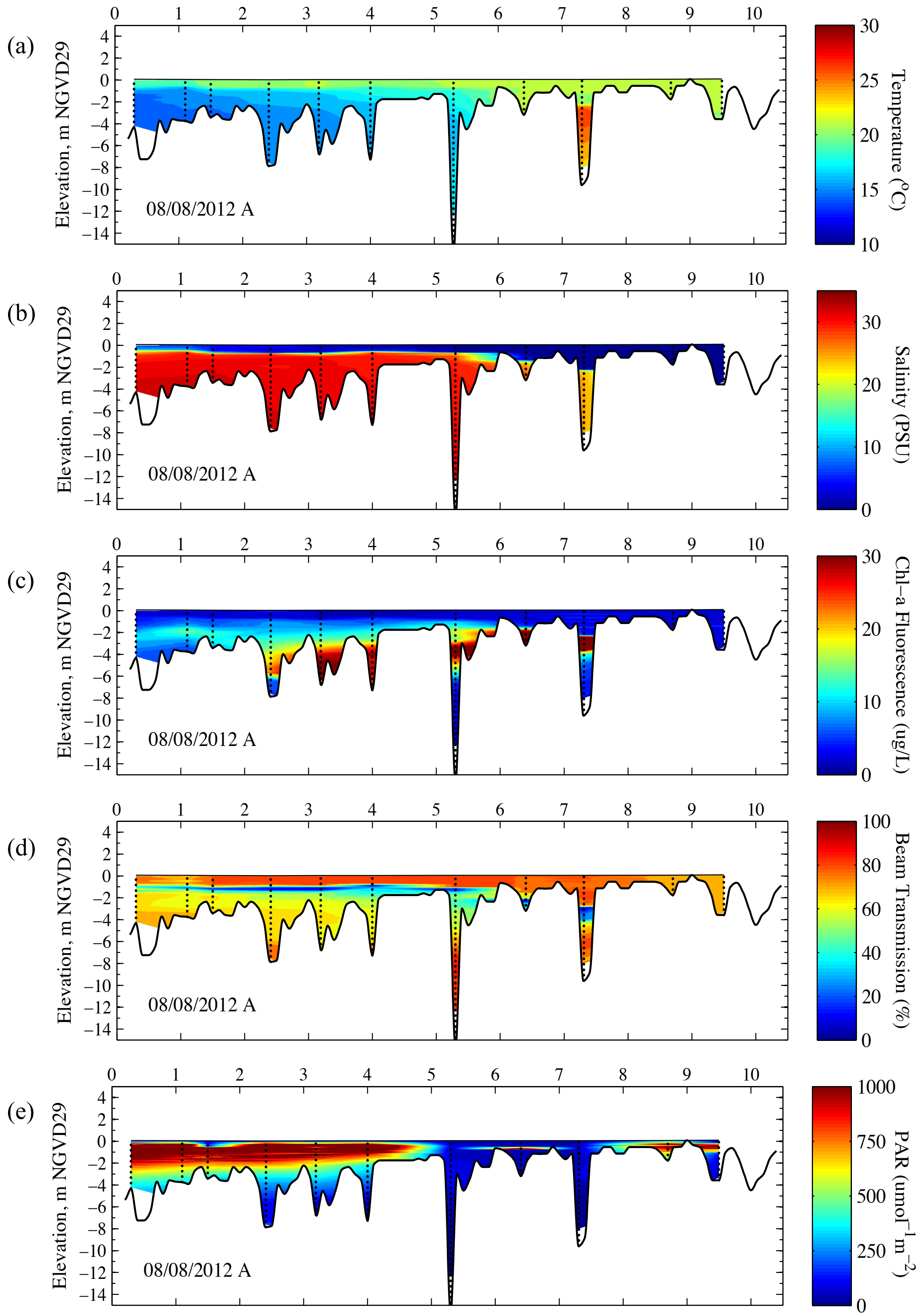

Figure 10.12 Contours of temperature (a), salinity (b), chlorophyll fluorescence (c), beam transmission (d), and PAR (e) collected on 8 August 2012, when conditions at the estuary mouth were tidal. The x-axis represents distance (in km) from the estuary mouth.

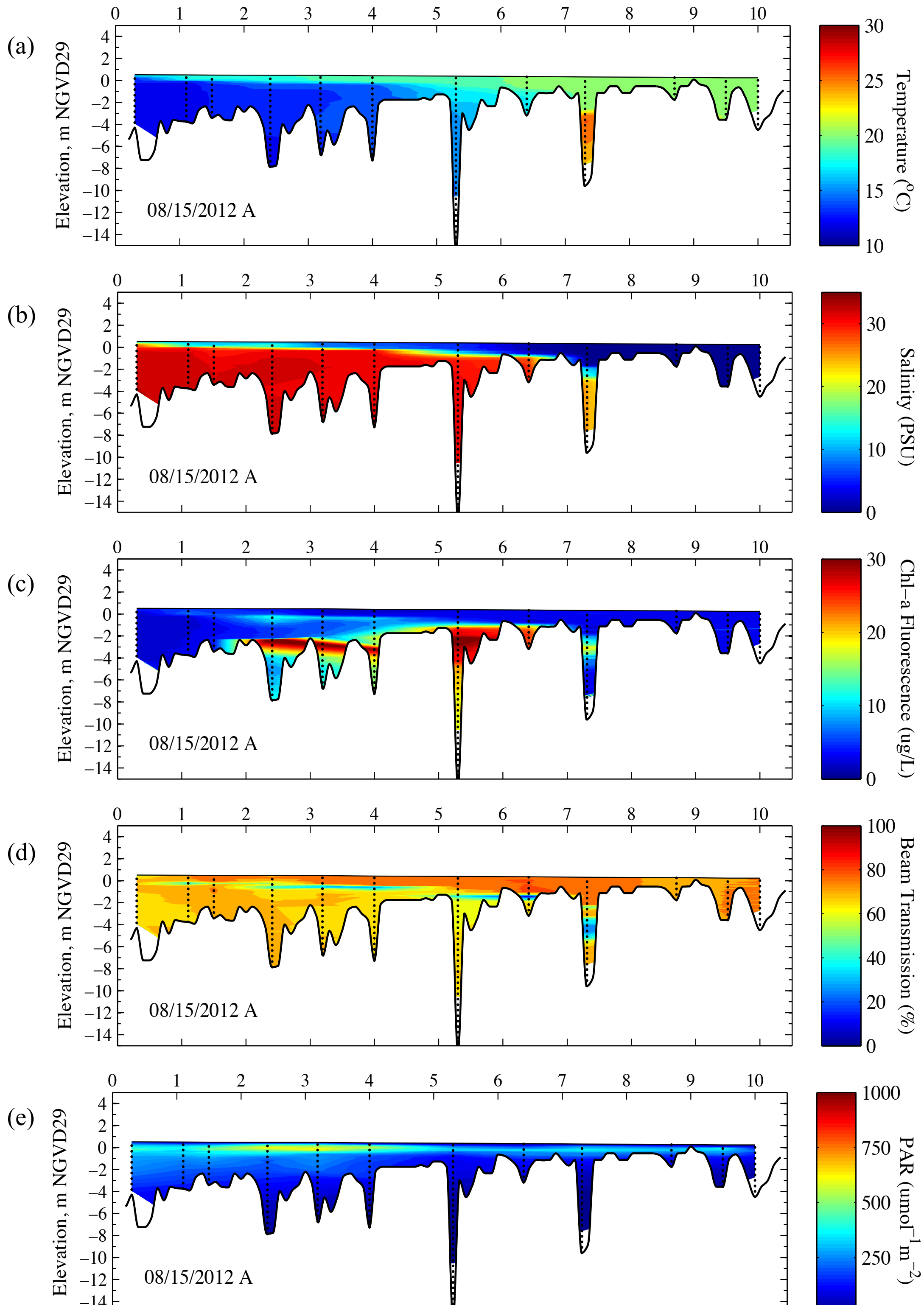

Figure 10.13 Contours of temperature (a), salinity (b), chlorophyll fluorescence (c), beam transmission (d), and PAR (e) collected on 15 August 2012, when conditions at the estuary mouth were tidal. The x-axis represents distance (in km) from the estuary mouth.

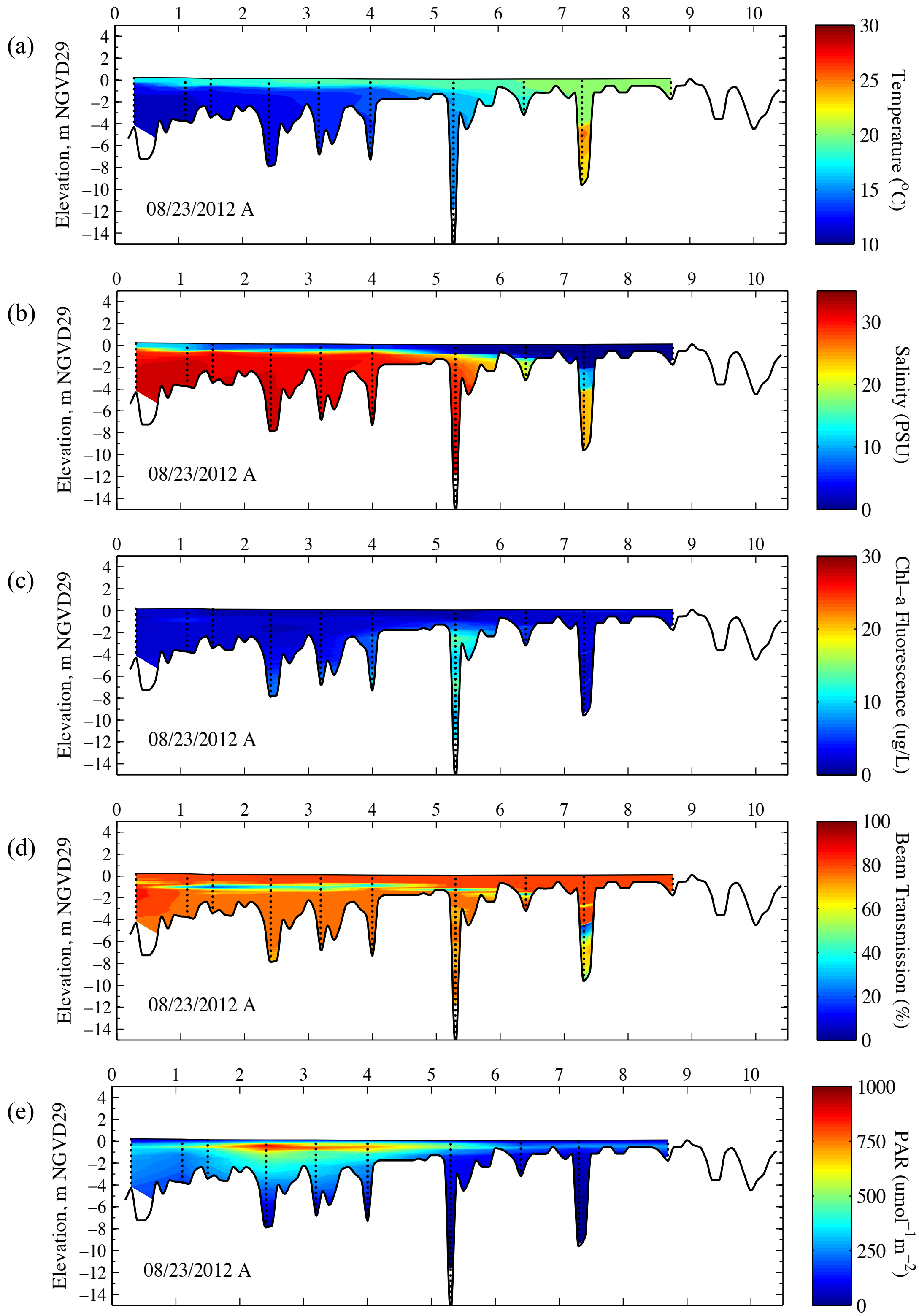

Figure 10.14 Contours of temperature (a), salinity (b), chlorophyll fluorescence (c), beam transmission (d), and PAR (e) collected on 23 August 2012, when conditions at the estuary mouth were tidal. The x-axis represents distance (in km) from the estuary mouth.

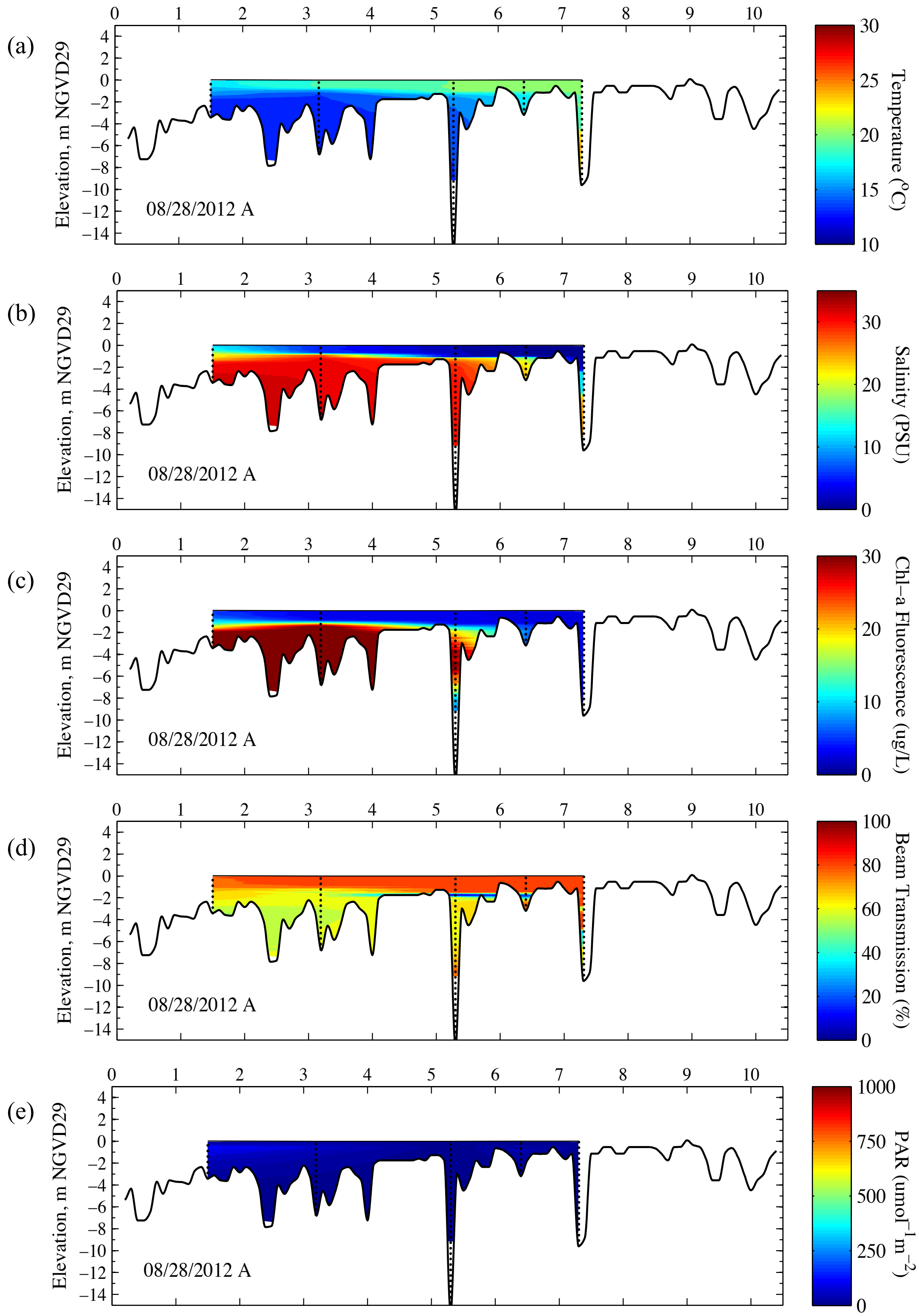

Figure 10.15 Contours of temperature (a), salinity (b), chlorophyll fluorescence (c), beam transmission (d), and PAR (e) collected during the sunrise transect on 28 August 2012, when conditions at the estuary mouth were tidal. The x-axis represents distance (in km) from the estuary mouth.

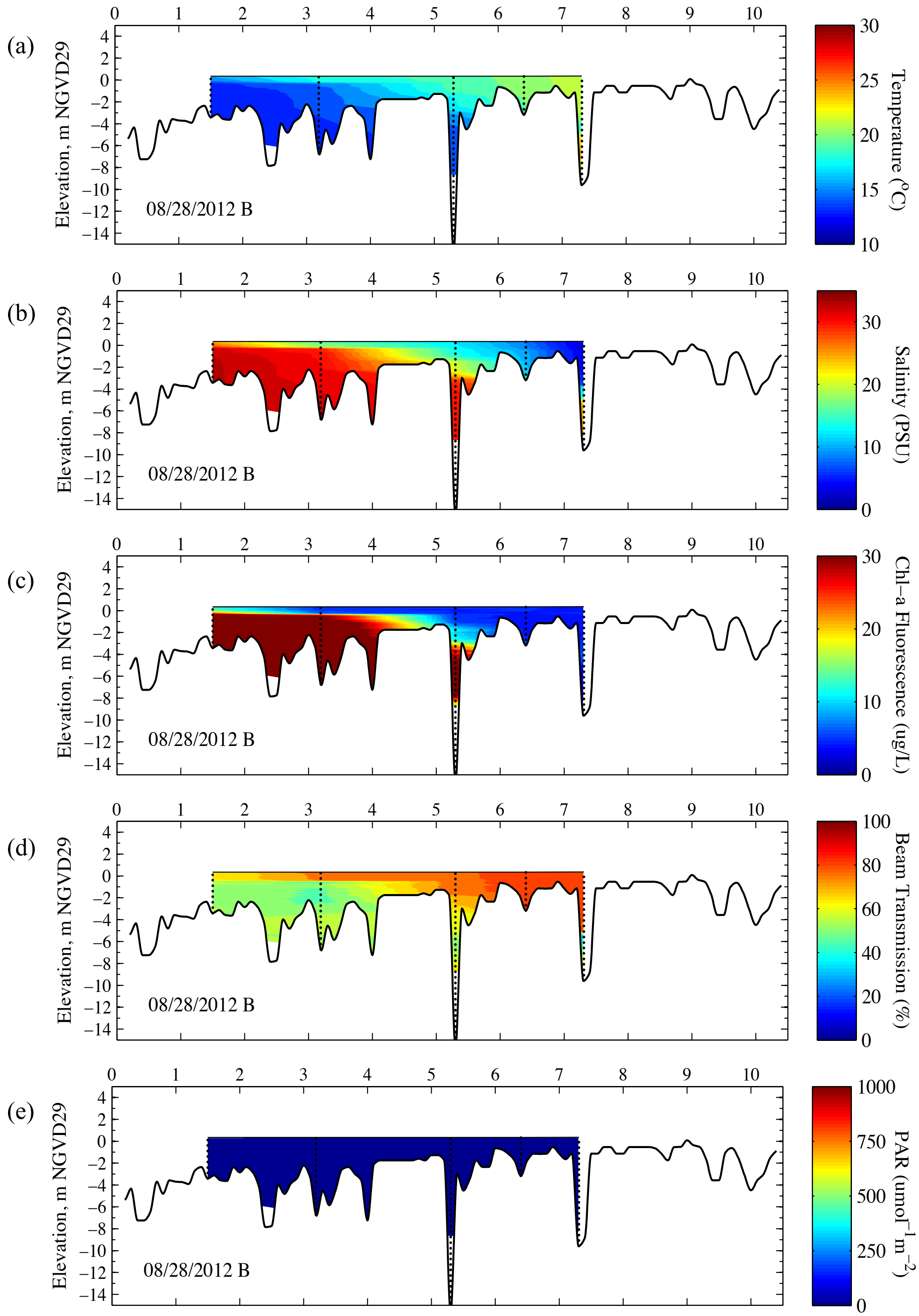

Figure 10.16 Contours of temperature (a), salinity (b), chlorophyll fluorescence (c), beam transmission (d), and PAR (e) collected during the sunset transect on 28 August 2012, when conditions at the estuary mouth were tidal. The x-axis represents distance (in km) from the estuary mouth.

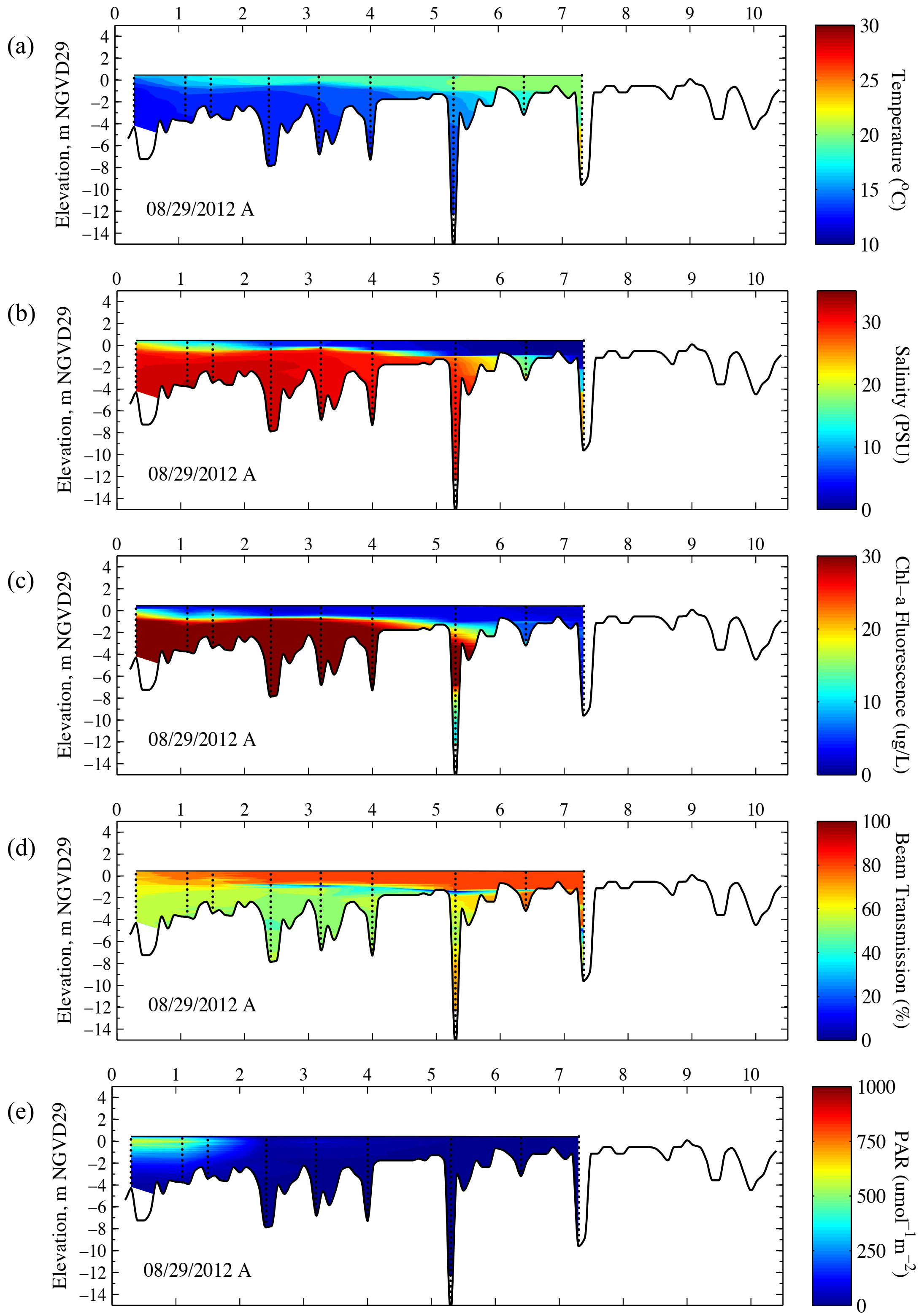

Figure 10.17 Contours of temperature (a), salinity (b), chlorophyll fluorescence (c), beam transmission (d), and PAR (e) collected during the sunrise transect on 29 August 2012, when conditions at the estuary mouth were tidal. The x-axis represents distance (in km) from the estuary mouth.

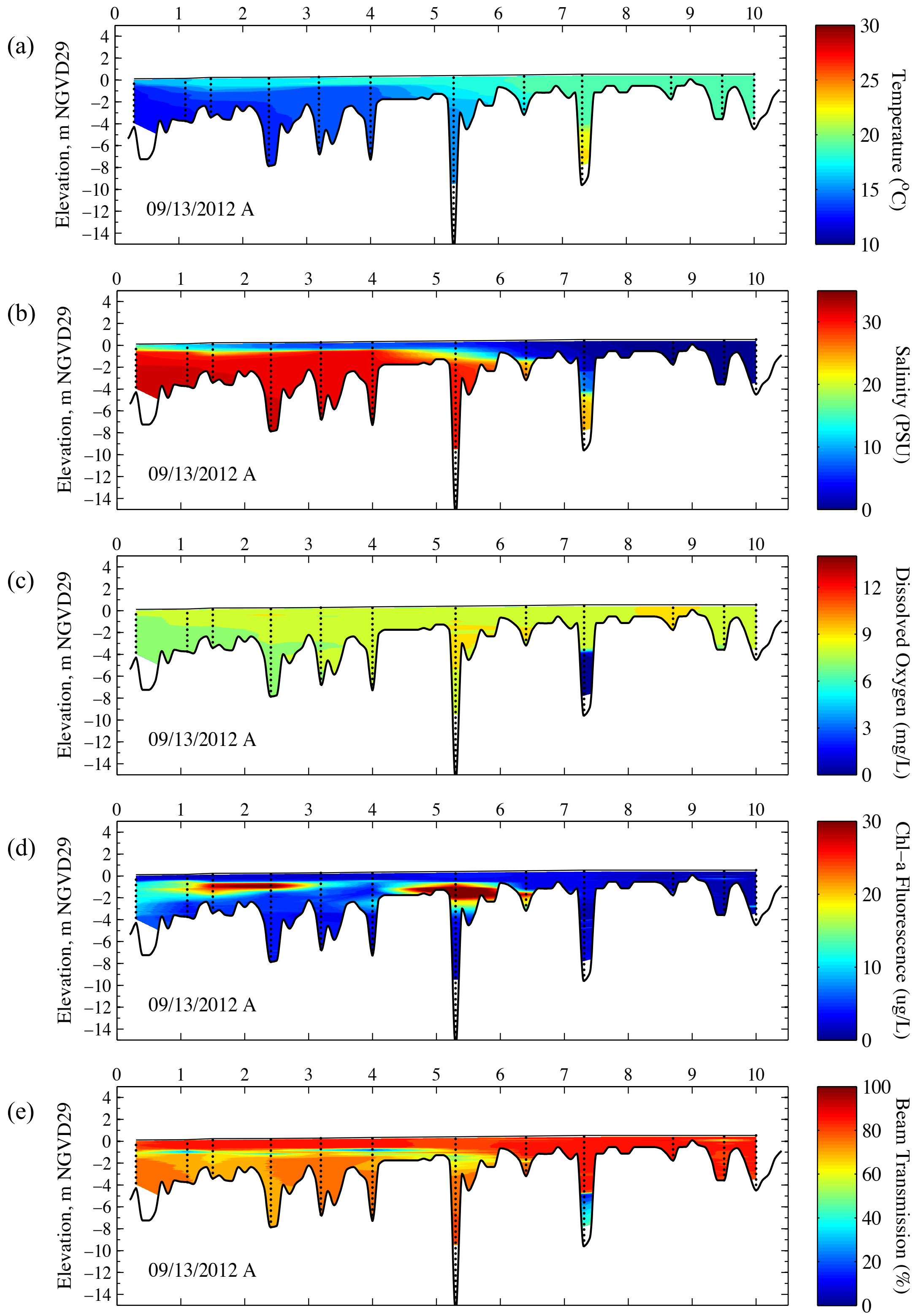

Figure 10.18 Contours of temperature (a), salinity (b), dissolved oxygen (c), chlorophyll fluorescence (d), and beam transmission (e) collected on 13 September 2012, when conditions at the estuary mouth were tidal. The x-axis represents distance (in km) from the estuary mouth.

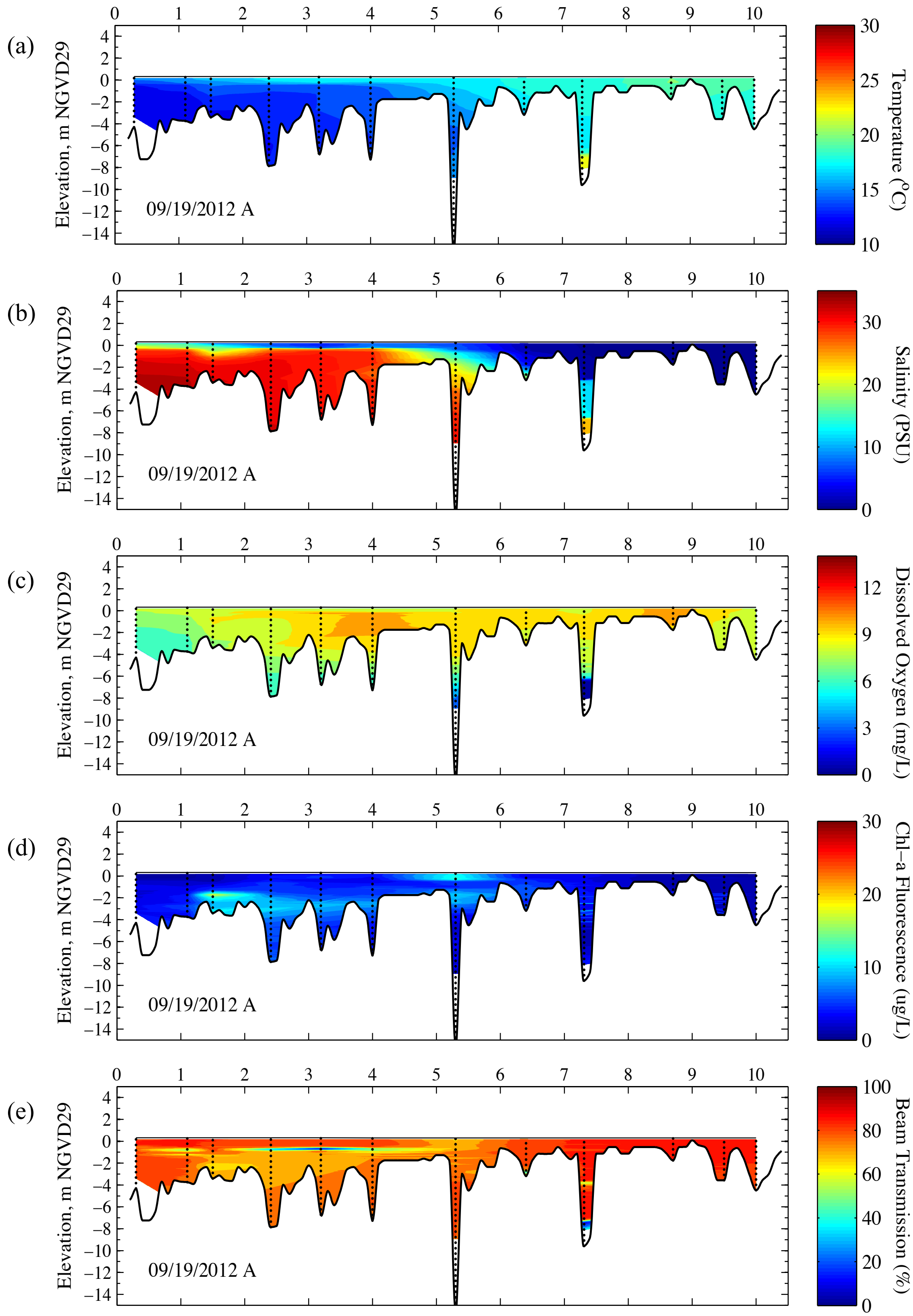

Figure 10.19 Contours of temperature (a), salinity (b), dissolved oxygen (c), chlorophyll fluorescence (d), and beam transmission (e) collected on 19 September 2012, when conditions at the estuary mouth were tidal. The x-axis represents distance (in km) from the estuary mouth.

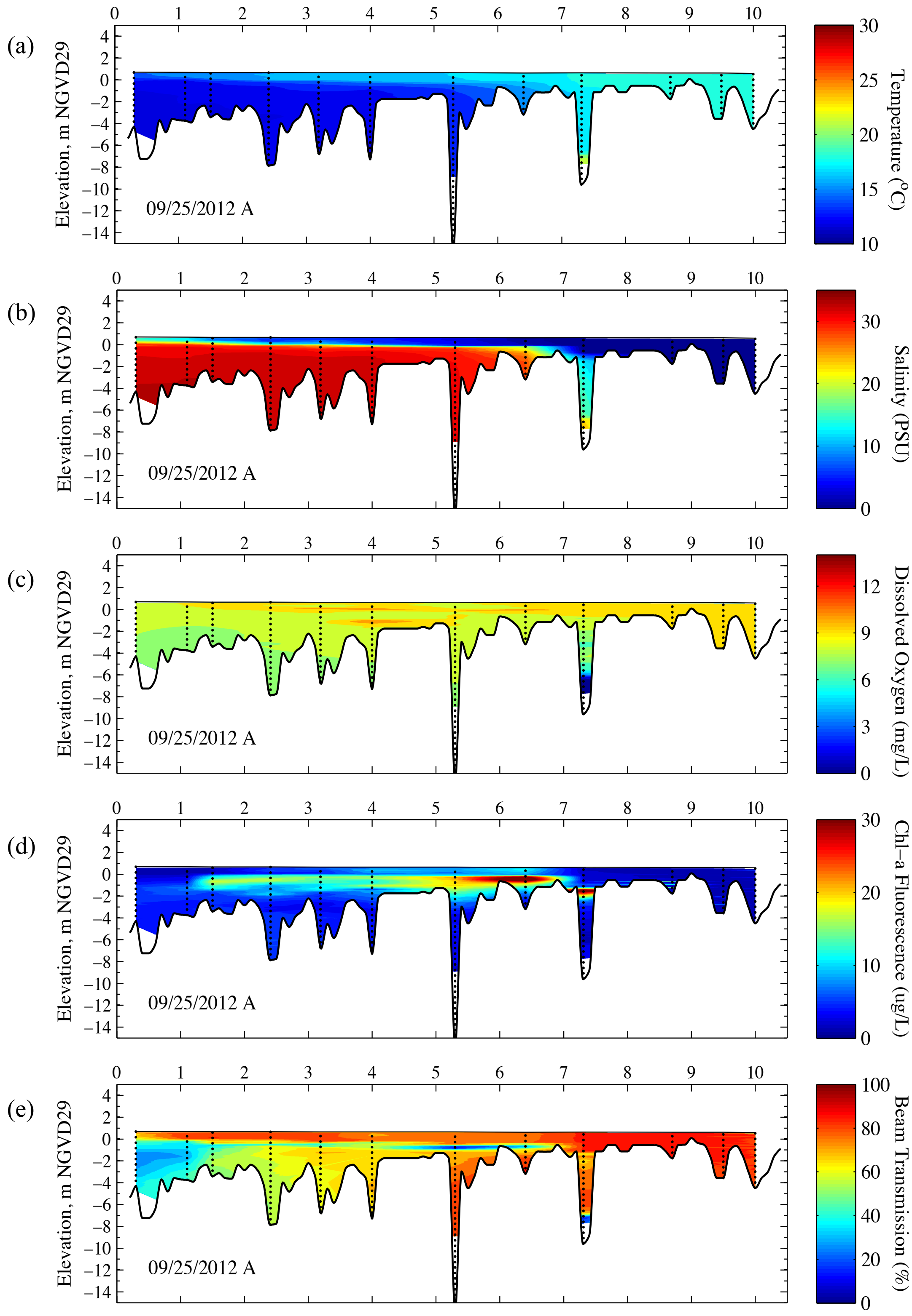

Figure 10.20 Contours of temperature (a), salinity (b), dissolved oxygen (c), chlorophyll fluorescence (d), and beam transmission (e) collected on 25 September 2012, when the estuary mouth was beginning to become constricted. The x-axis represents distance (in km) from the estuary mouth.

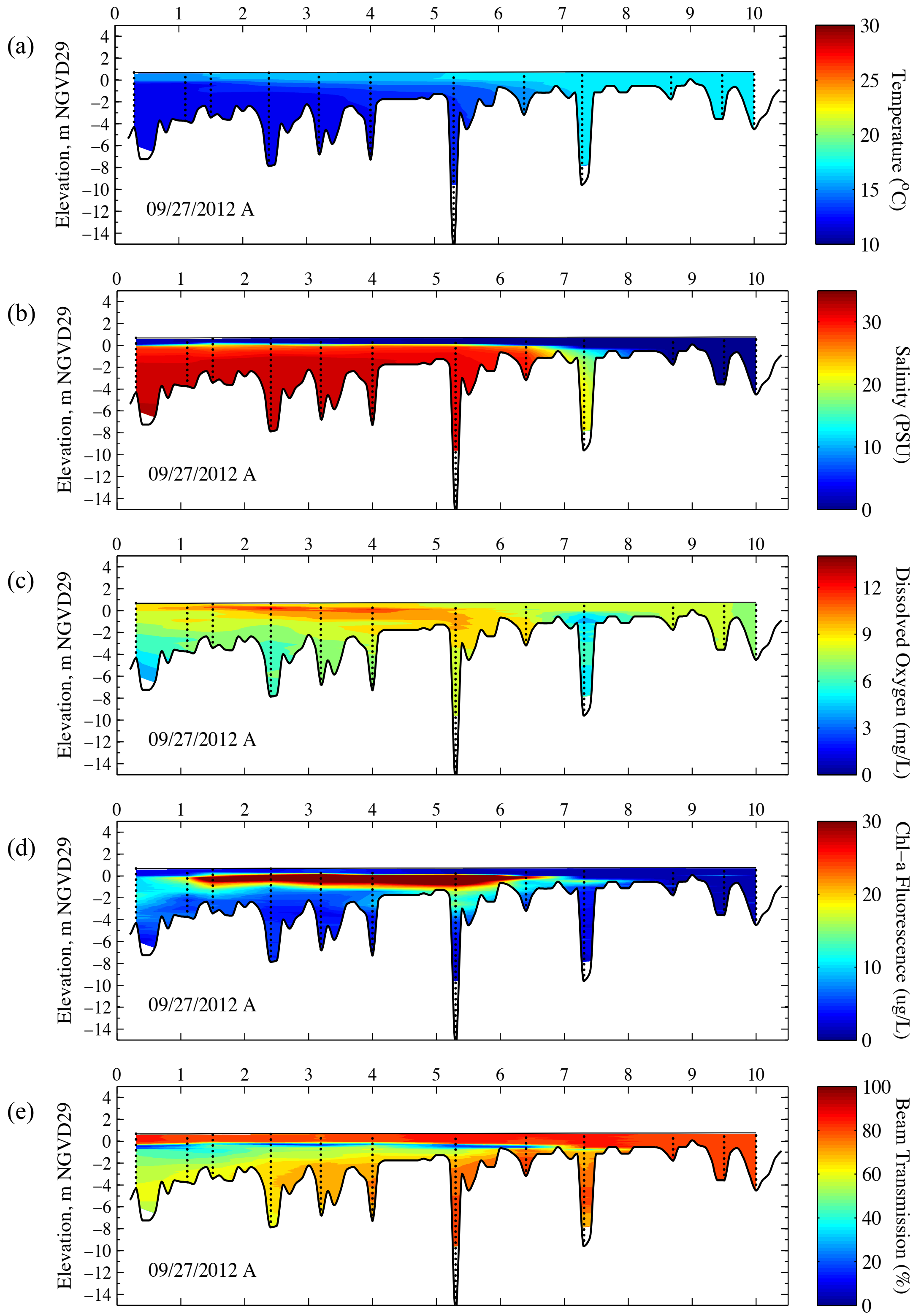

Figure 10.21 Contours of temperature (a), salinity (b), dissolved oxygen (c), chlorophyll fluorescence (d), and beam transmission (e) collected on 27 September 2012, when the estuary mouth had been constricted for approximately 2 days. The x-axis represents distance (in km) from the estuary mouth.

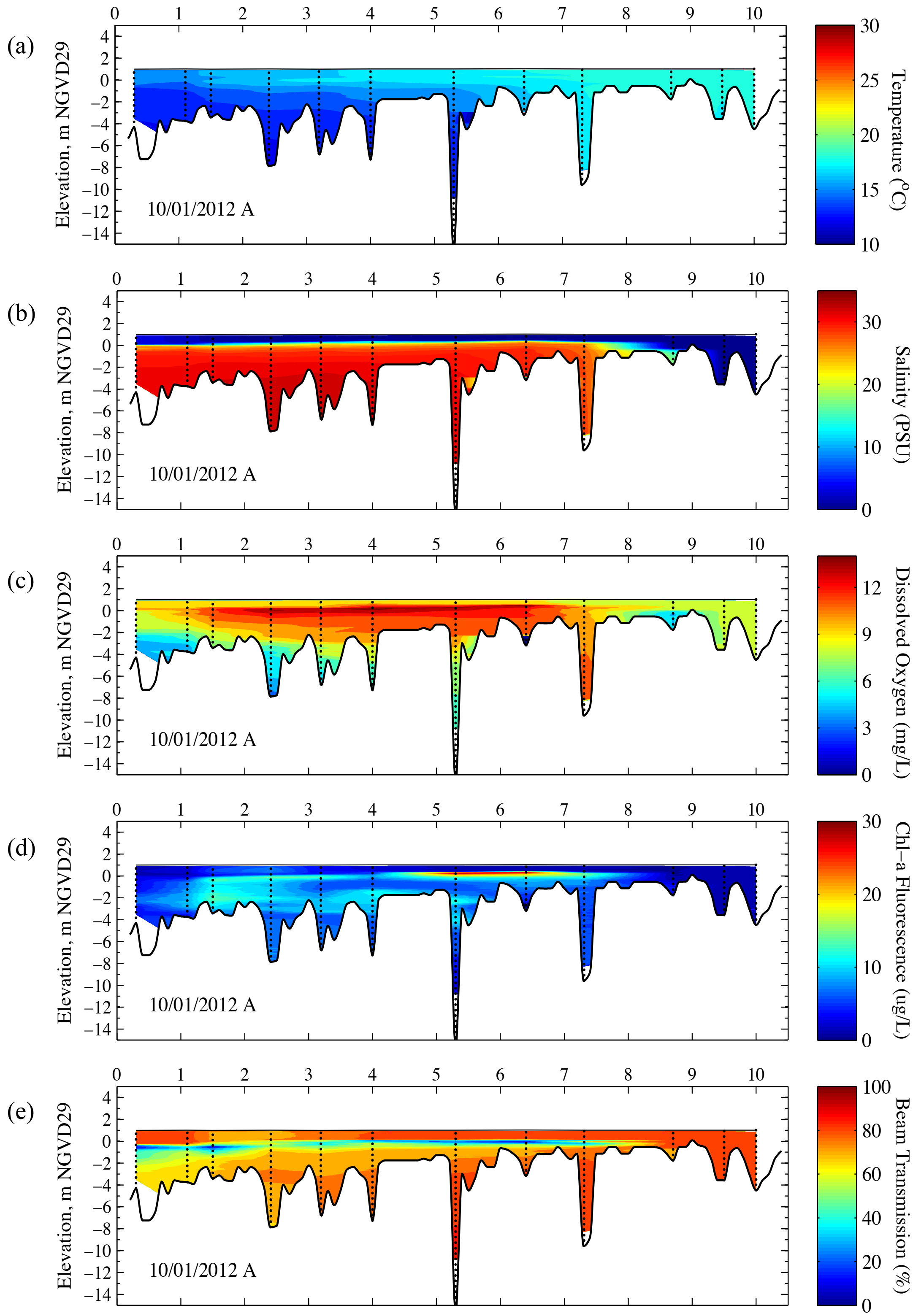

Figure 10.22 Contours of temperature (a), salinity (b), dissolved oxygen (c), chlorophyll fluorescence (d), and beam transmission (e) collected on 1 October 2012, when the estuary mouth had been closed for approximately 2 days. The x-axis represents distance (in km) from the estuary mouth.

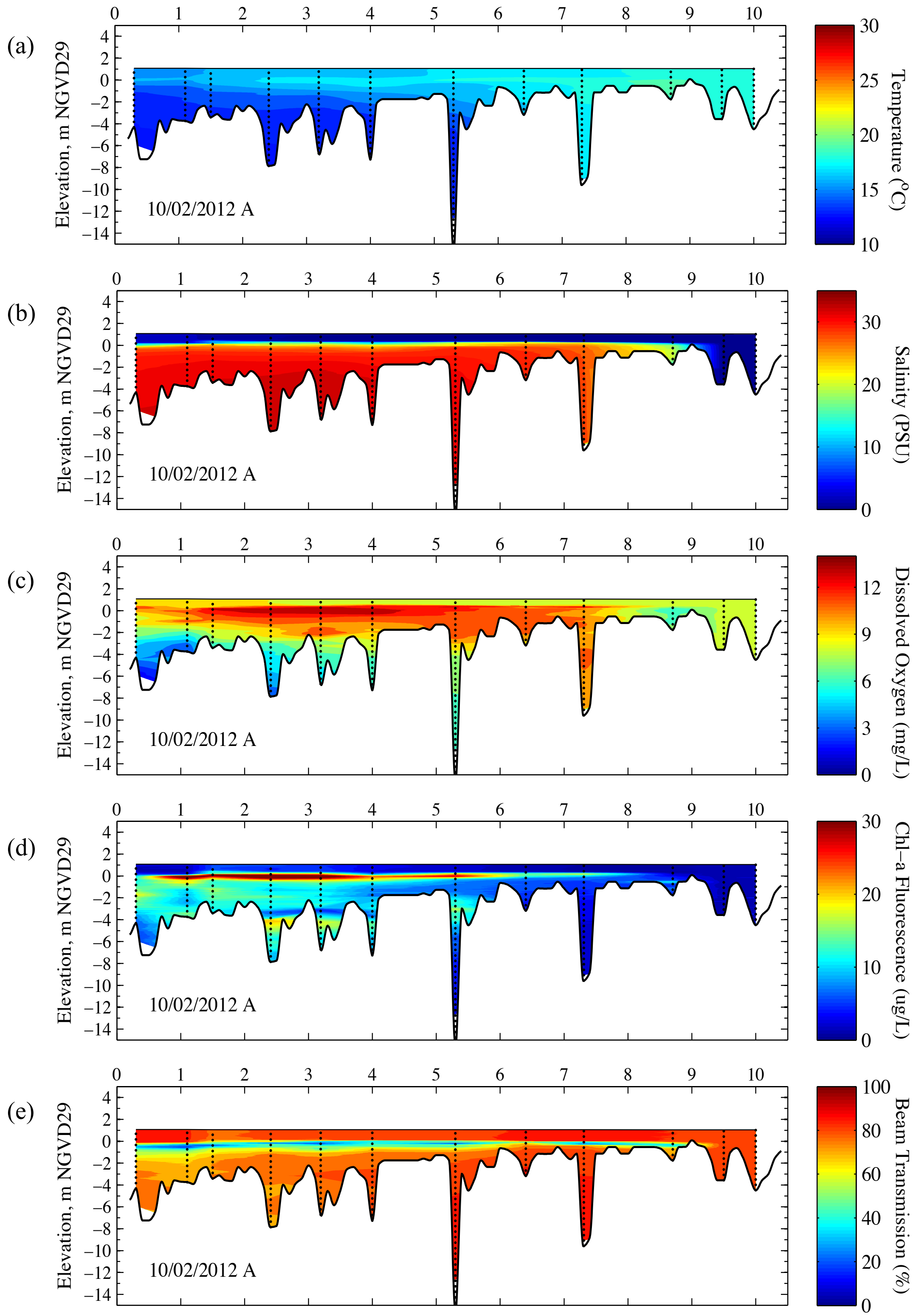

Figure 10.23 Contours of temperature (a), salinity (b), dissolved oxygen (c), chlorophyll fluorescence (d), and beam transmission (e) collected on 2 October 2012, when the estuary mouth had been closed for approximately 3 days. The x-axis represents distance (in km) from the estuary mouth.

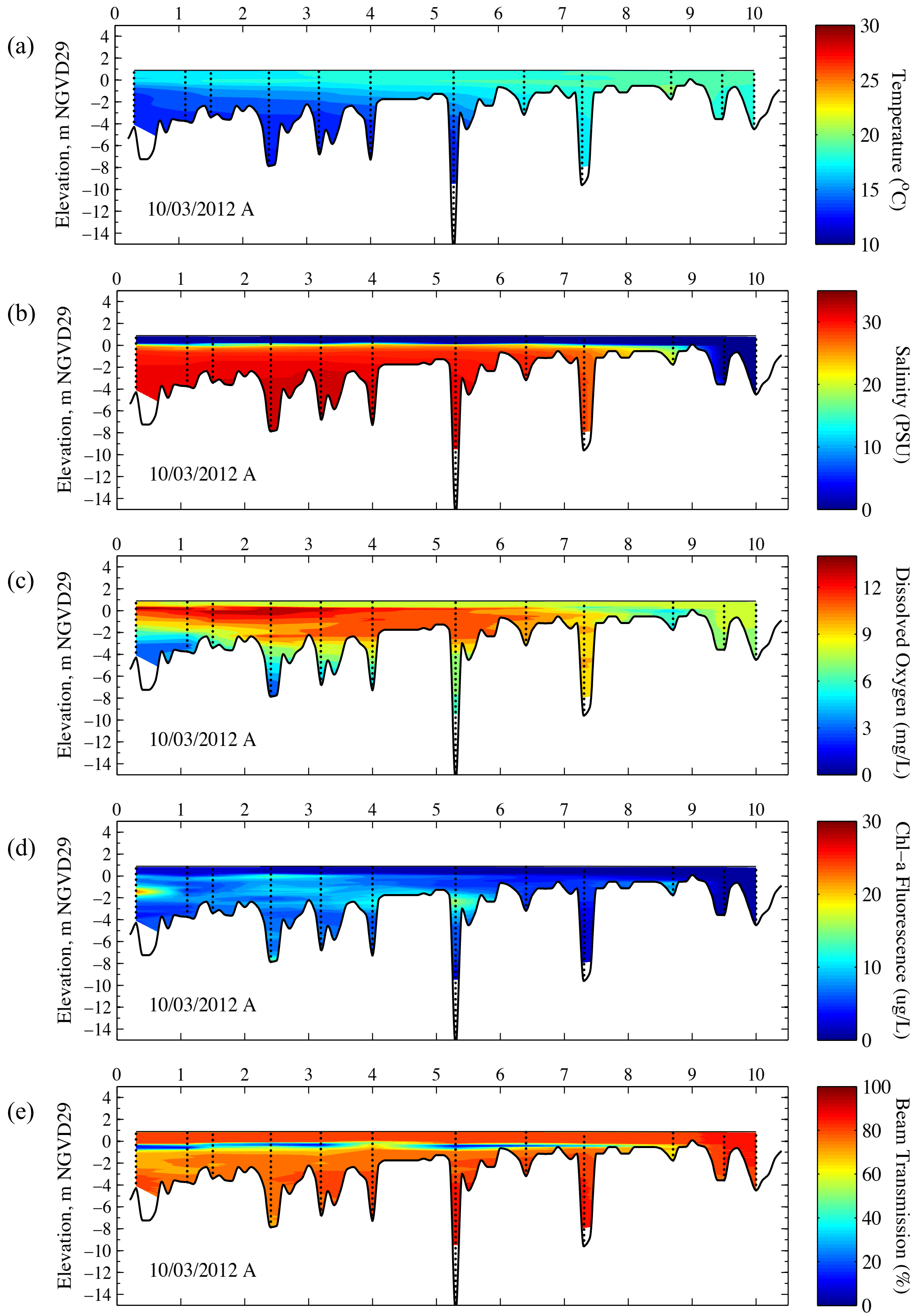

Figure 10.24 Contours of temperature (a), salinity (b), dissolved oxygen (c), chlorophyll fluorescence (d), and beam transmission (e) collected on 3 October 2012, when the estuary mouth had been closed for approximately 4 days. The x-axis represents distance (in km) from the estuary mouth.

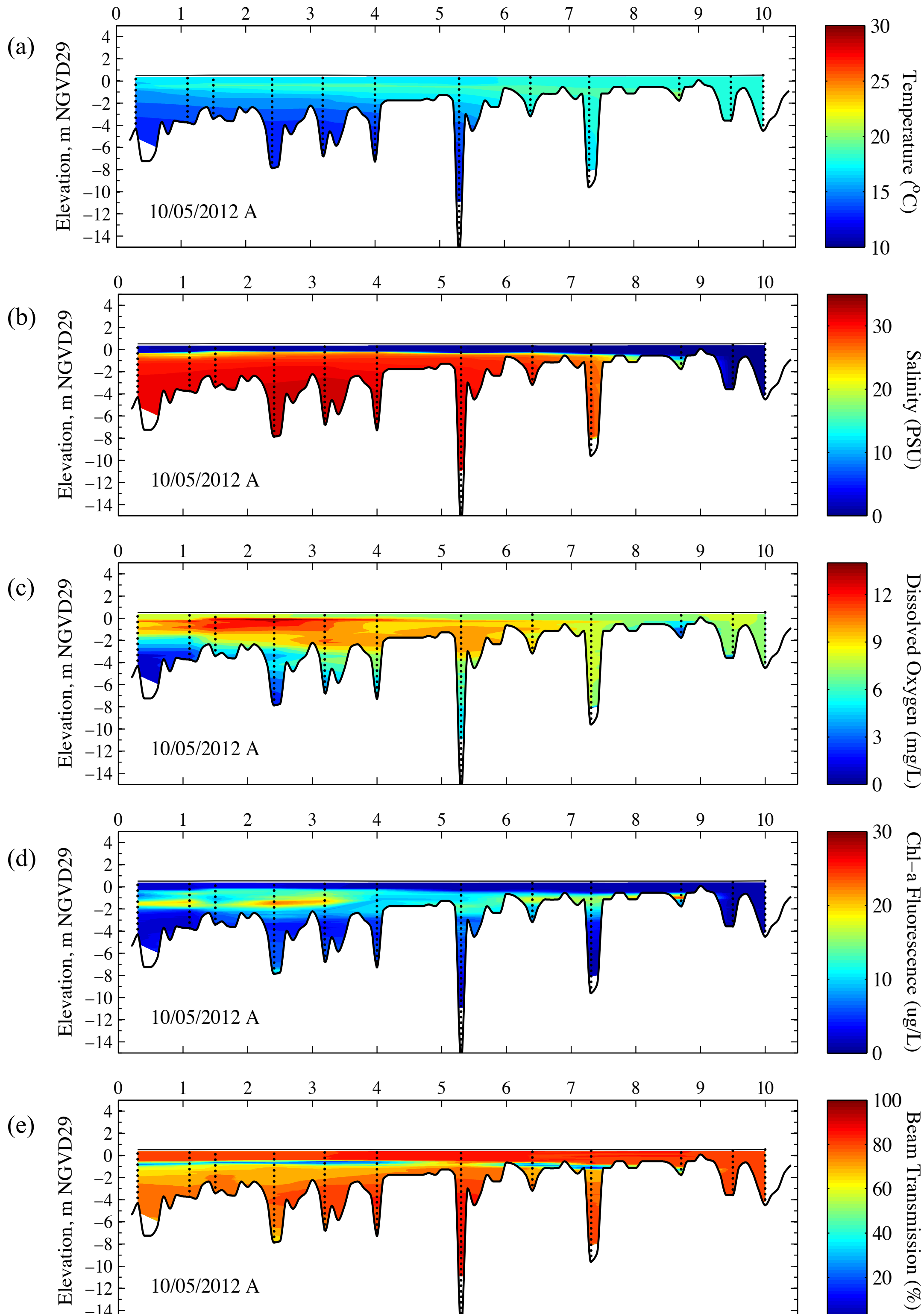

Figure 10.25 Contours of temperature (a), salinity (b), dissolved oxygen (c), chlorophyll fluorescence (d), and beam transmission (e) collected on 5 October 2012, when conditions at the estuary mouth were weakly tidal. The x-axis represents distance (in km) from the estuary mouth.

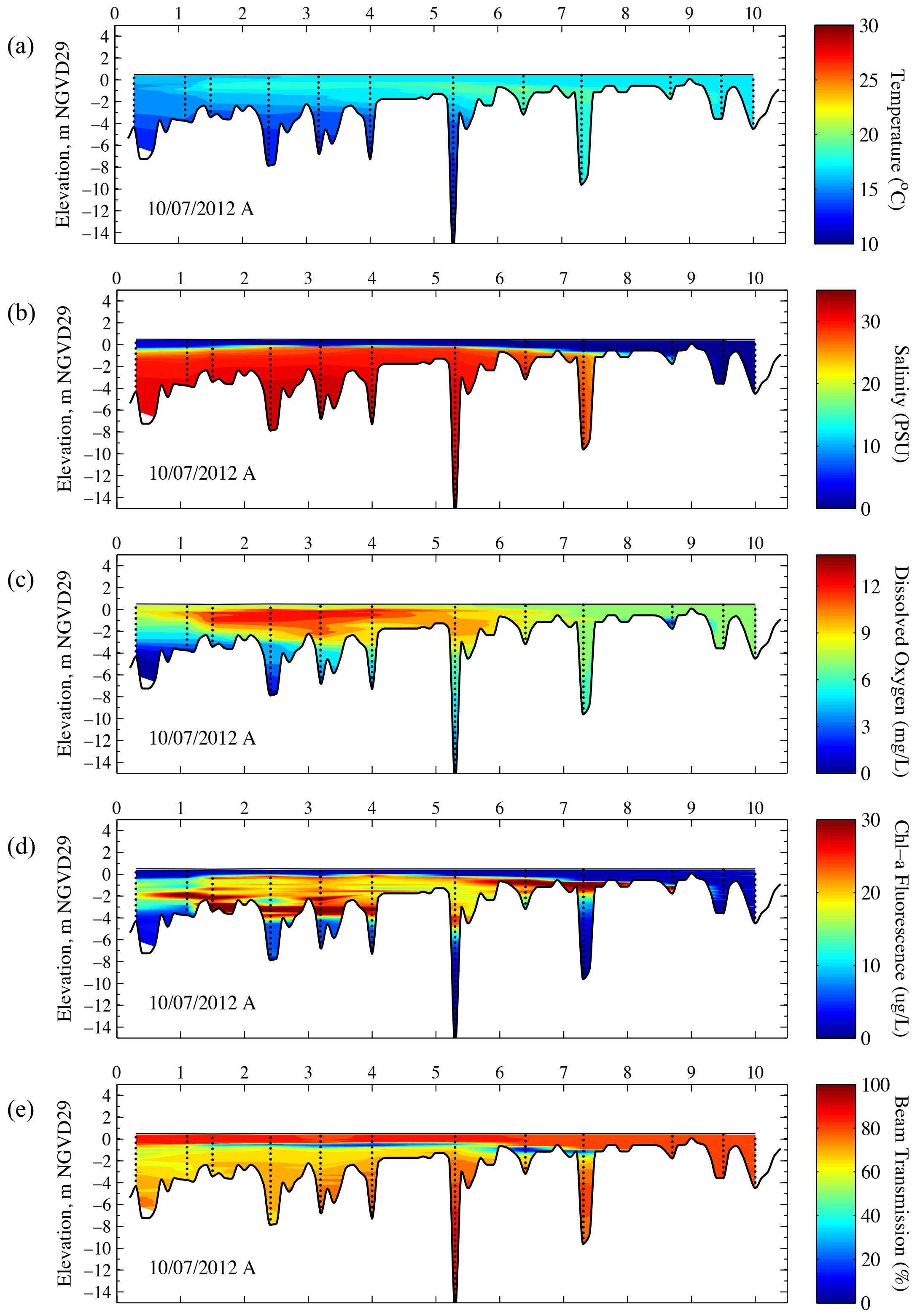

Figure 10.26 Contours of temperature (a), salinity (b), dissolved oxygen (c), chlorophyll fluorescence (d), and beam transmission (e) collected on 7 October 2012, when conditions at the estuary mouth were weakly tidal. The x-axis represents distance (in km) from the estuary mouth.

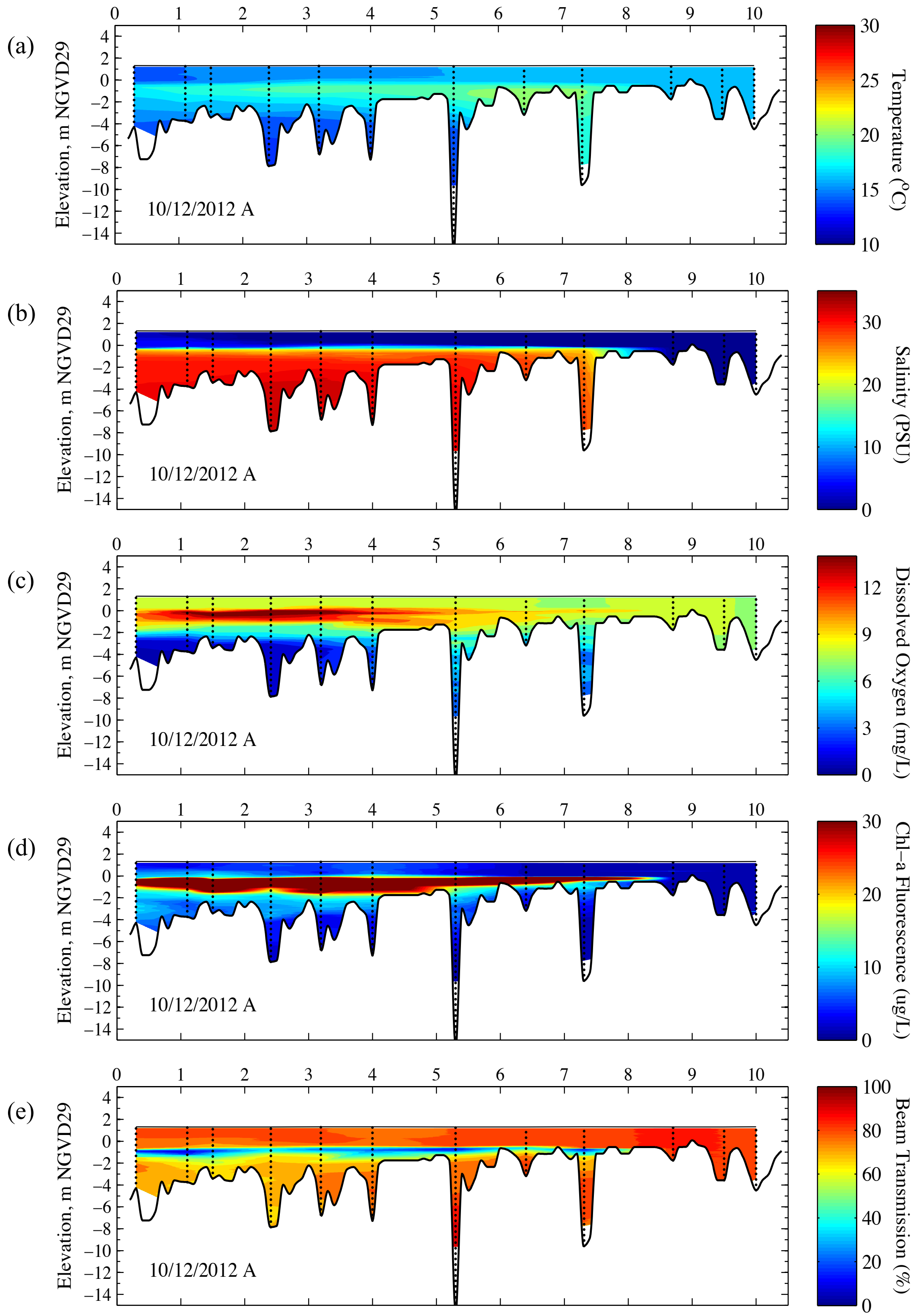

Figure 10.27 Contours of temperature (a), salinity (b), dissolved oxygen (c), chlorophyll fluorescence (d), and beam transmission (e) collected on 12 October 2012, when the estuary mouth had been closed for 4 days. The x-axis represents distance (in km) from the estuary mouth.

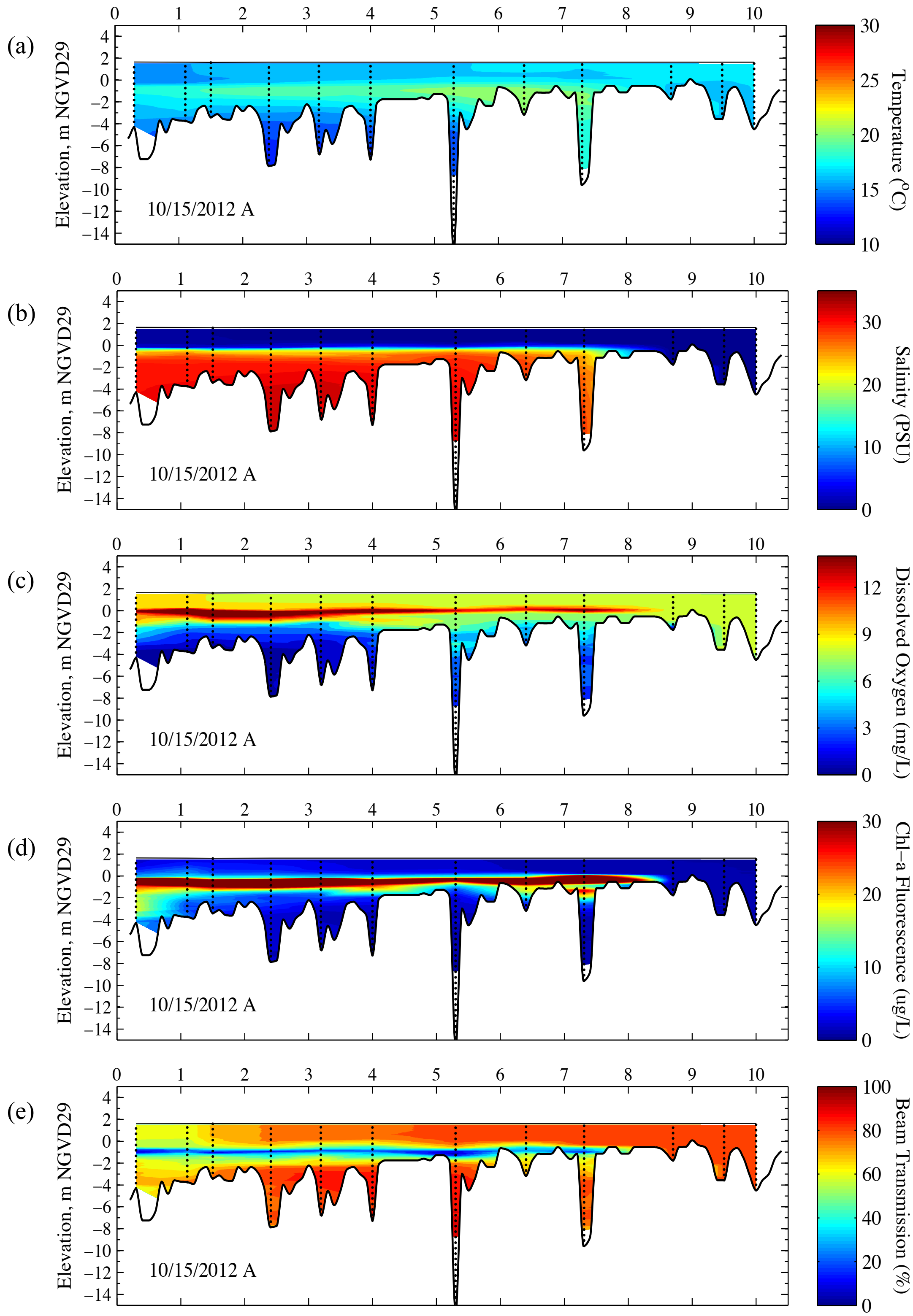

Figure 10.28 Contours of temperature (a), salinity (b), dissolved oxygen (c), chlorophyll fluorescence (d), and beam transmission (e) collected on 15 October 2012, when the estuary mouth had been closed for 7 days. The x-axis represents distance (in km) from the estuary mouth.

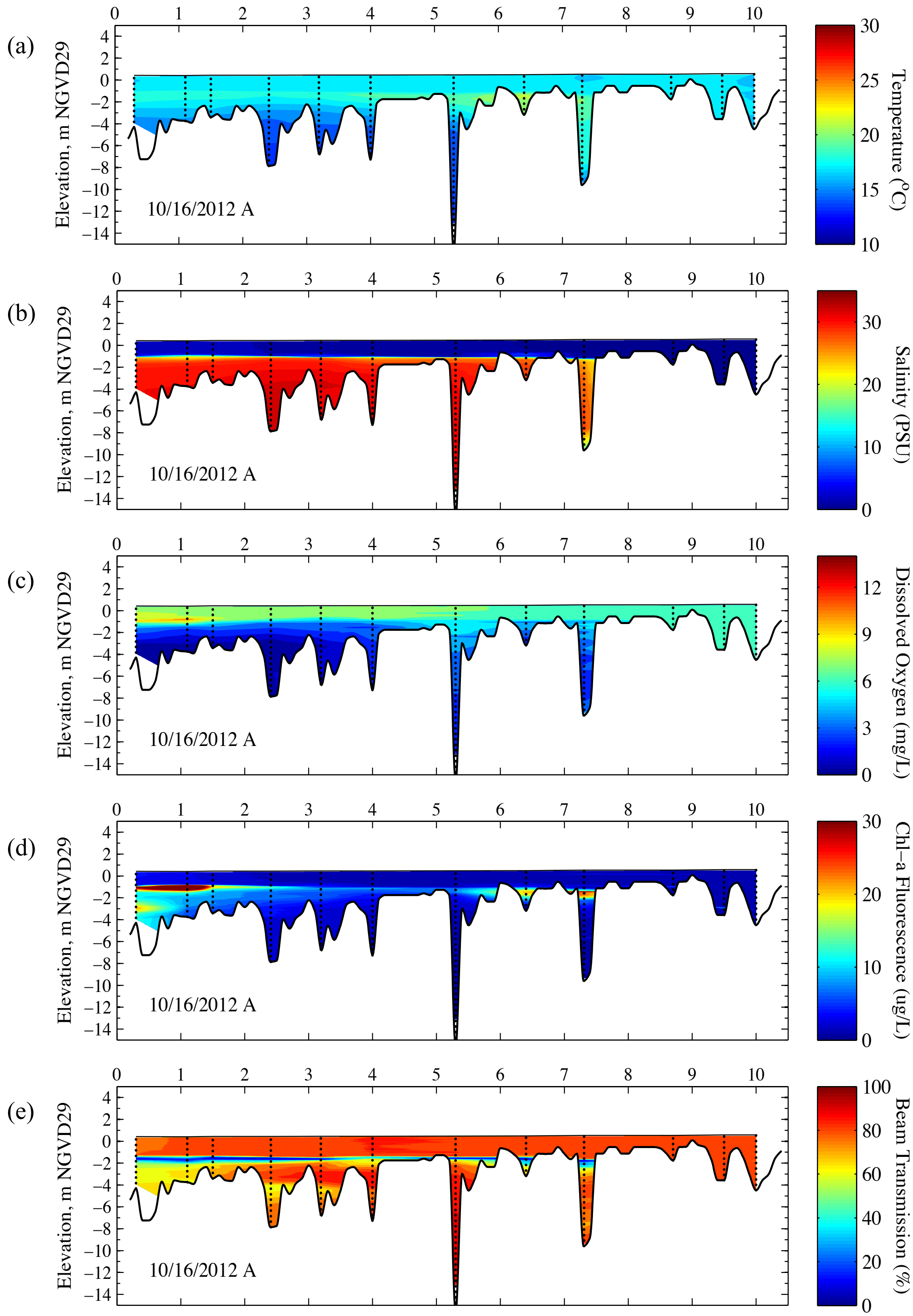

Figure 10.29 Contours of temperature (a), salinity (b), dissolved oxygen (c), chlorophyll fluorescence (d), and beam transmission (e) collected on 16 October 2012, just after the estuary mouth self-breached. The x-axis represents distance (in km) from the estuary mouth.

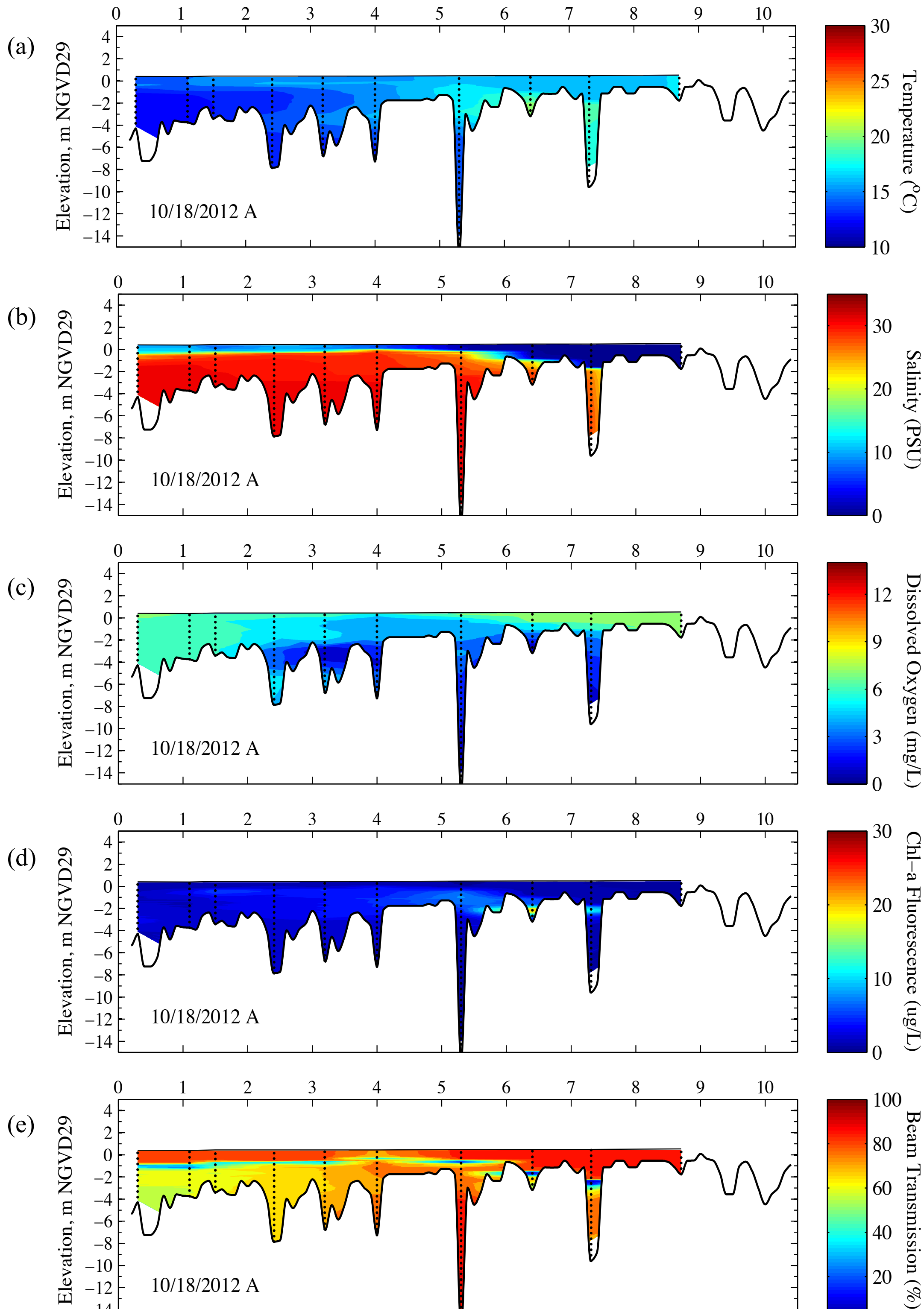

Figure 10.30 Contours of temperature (a), salinity (b), dissolved oxygen (c), chlorophyll fluorescence (d), and beam transmission (e) collected on 18 October 2012, when conditions at the mouth had been tidal for approximately 2 days. The x-axis represents distance (in km) from the estuary mouth.

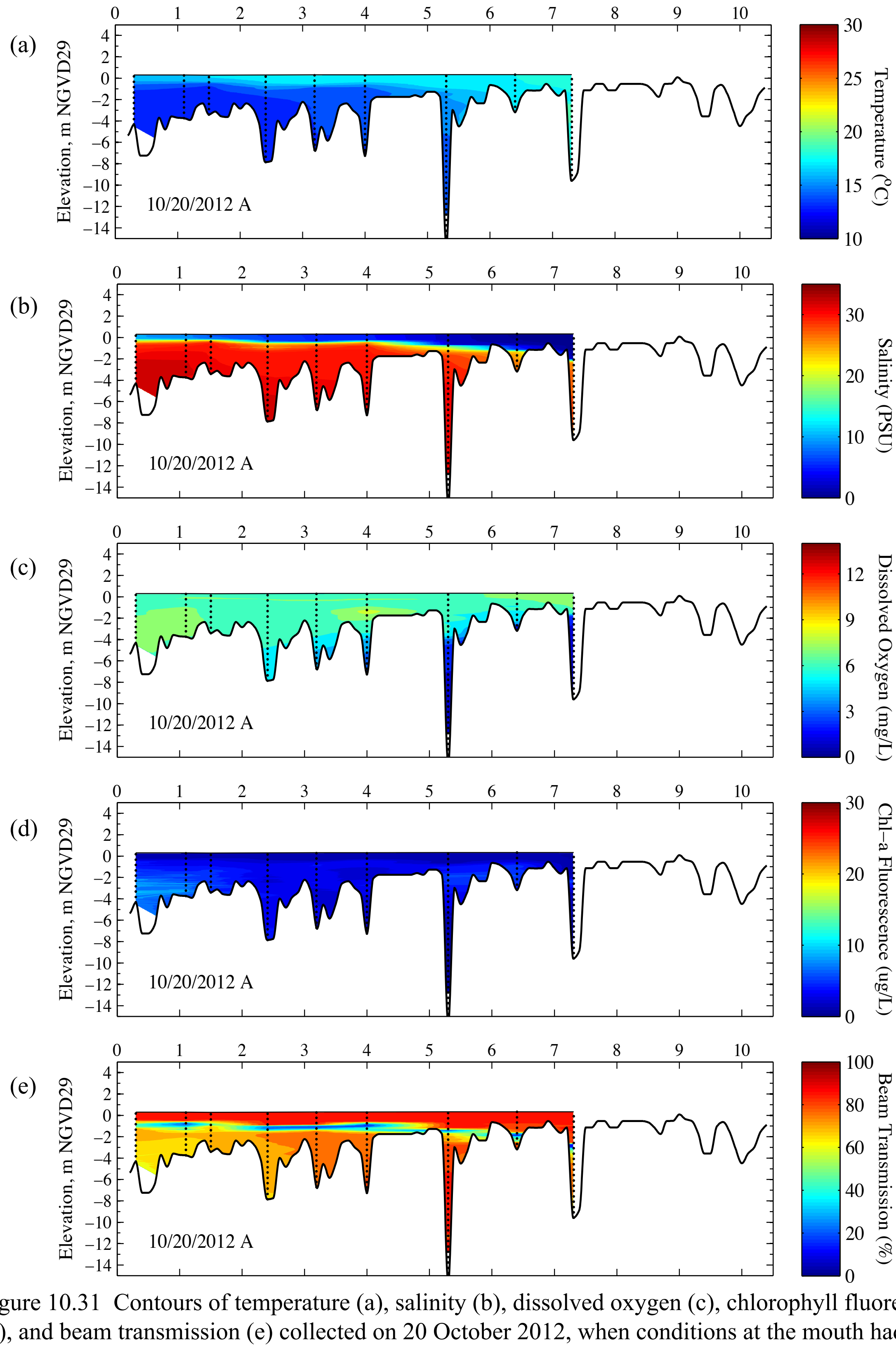

Figure 10.31 Contours of temperature (a), salinity (b), dissolved oxygen (c), chlorophyll fluorescence (d), and beam transmission (e) collected on 20 October 2012, when conditions at the mouth had been tidal for approximately 4 days. The x-axis represents distance (in km) from the estuary mouth.

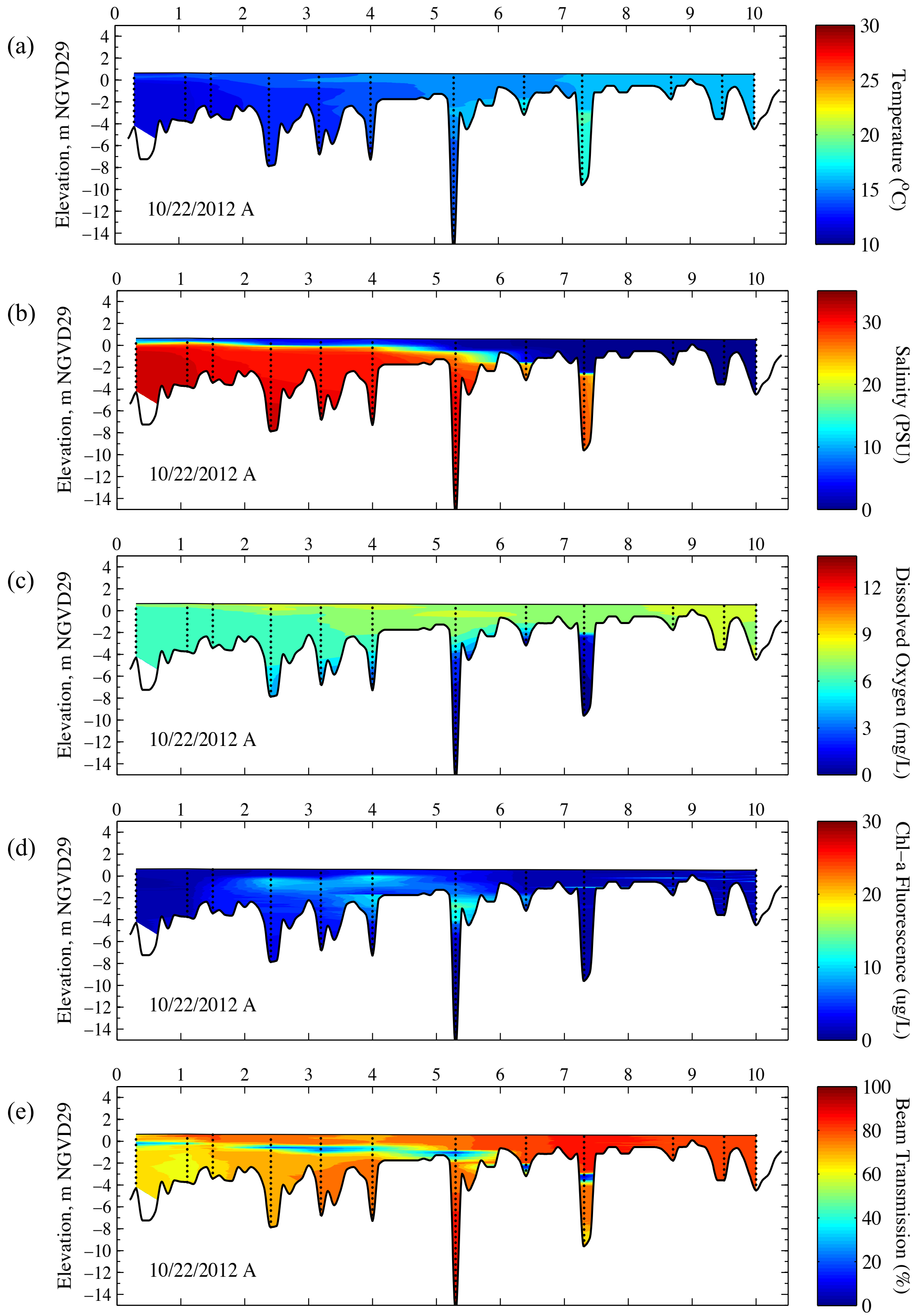

Figure 10.32 Contours of temperature (a), salinity (b), dissolved oxygen (c), chlorophyll fluorescence (d), and beam transmission (e) collected on 22 October 2012, when conditions at the mouth had been tidal for approximately 6 days. The x-axis represents distance (in km) from the estuary mouth.