RISE 2 – R/V Pt Sur Cruise Report

By David A. Jay, OGI/OHSU
Alex Horner-Devine, UW
Jiayi Pan, OGI/OHSU
Jay Peterson, NOAA Fisheries
Philip Orton, Lamont-Doherty

Aaron Raciot, OGI/OHSU

Purpose and Context

RISE hypothesizes that the Columbia River plume is more productive than adjacent coastal waters, that it facilitates cross-margin transport of particles and biota, and that the iron supplied by the plume is important to Pacific Northwest coastal primarily production, especially off Washington. Understanding the impact of the highly mobile Columbia River plume on coastal production and transport patterns requires that measurements be made on a variety of scales from turbulence to internal waves and fronts, to those of the plume and the underlying shelf circulation. RISE emphasizes, therefore, rapid surveys with the Triaxus towfish and detailed process investigations.

The RISE field program consists of two high-flow cruises (spring 2005 and 2006), one medium-flow cruise (July 2004) and one low-flow cruise (August 2005). Each cruise is to be carried out by two vessels, the R/V Wecoma (biological and chemical studies) and the R/V Pt Sur (plume surveys, mixing processes and zooplankton dynamics).

The first RISE cruise (RISE 1) in July 2004 was partially an exploratory venture, testing our approach to project hypotheses, and the suitability of sampling gear to the environments. An important conclusion from RISE 1 was that the turbulence and Triaxus sampling modes were fundamentally incompatible. Thus, 2005 sampling consists of one Triaxus cruise (RISE 2, June 2005) and one turbulence cruise (RISE 3, August 2003). As with RISE 1, RISE 2 was supported by a prior estuary cruise by the Jay group. The purpose of the estuarine cruise was to understand the estuarine conditions at the origin of the plume, and estuarine particle properties.

The seasonal precipitation and flow patterns prior to RISE 2 were somewhat unusual. Sub-normal early winter precipitation (November and December) was followed by very dry conditions in January to mid-March. Precipitation from Mid-March through June was well above average in the Columbia western sub-basin. Discharge of the Columbia River at Beaver (at the head of the estuary, 86 km from the ocean) peaked just before the cruise (on 24 May), about three weeks earlier than average (Figure 1a). Due to high spring rainfall, the freshet peak (10,000 m^3s^{-1}) was only slightly below the average for the last 15 years, despite the dry winter. Because of the early freshet, flows were slightly above seasonal mean up to the beginning of the cruise, but declined below normal levels as the cruise progressed, being ~25% below average for most of the cruise. This flow level is about half the historic (pre-dam) flow for the freshet season. There were two aspects of the unusual discharge pattern that were relevant to RISE 2:

- Western sub-basin flows were well above average for May and June, being almost twice normal in the Willamette River just before the cruise (Figure 1b).

- The peak flow from the Upper Columbia was early (early May) and small (due to low reservoir levels), so that the Snake River peak flow occurred after that from the Upper Columbia. While this was primarily an effect of flow regulation, it was also related the relatively good snowpack in some parts of the Snake River basin versus a low snowpeak elsewhere in the Columbia Basin. Thus, flows for the two weeks prior to the cruise and during the first week of the cruise had an unusually high contribution from of Willamette and Snake River waters.

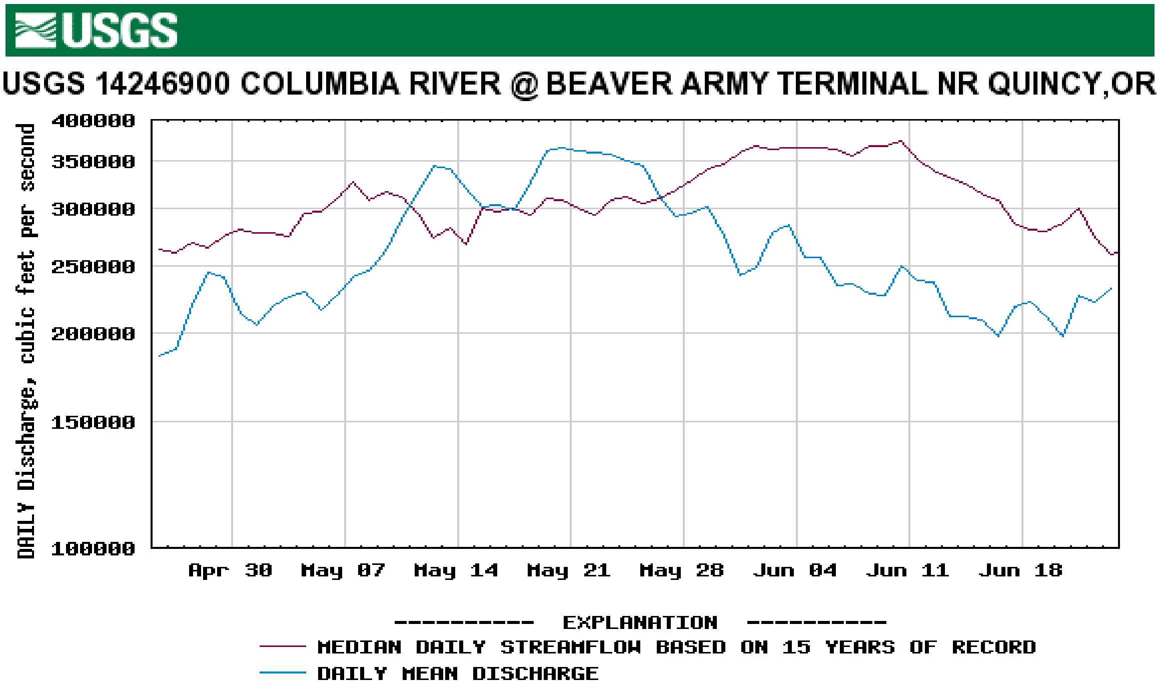


Figure 1a: Daily Columbia River flow at Beaver, (86 km from the ocean) in ft^3s^{-1}. The flow measured at Beaver combines flows from the Interior Sub-Basin east of the Cascade Mountains with the major west-side tributaries, including the Willamette and Cowlitz.

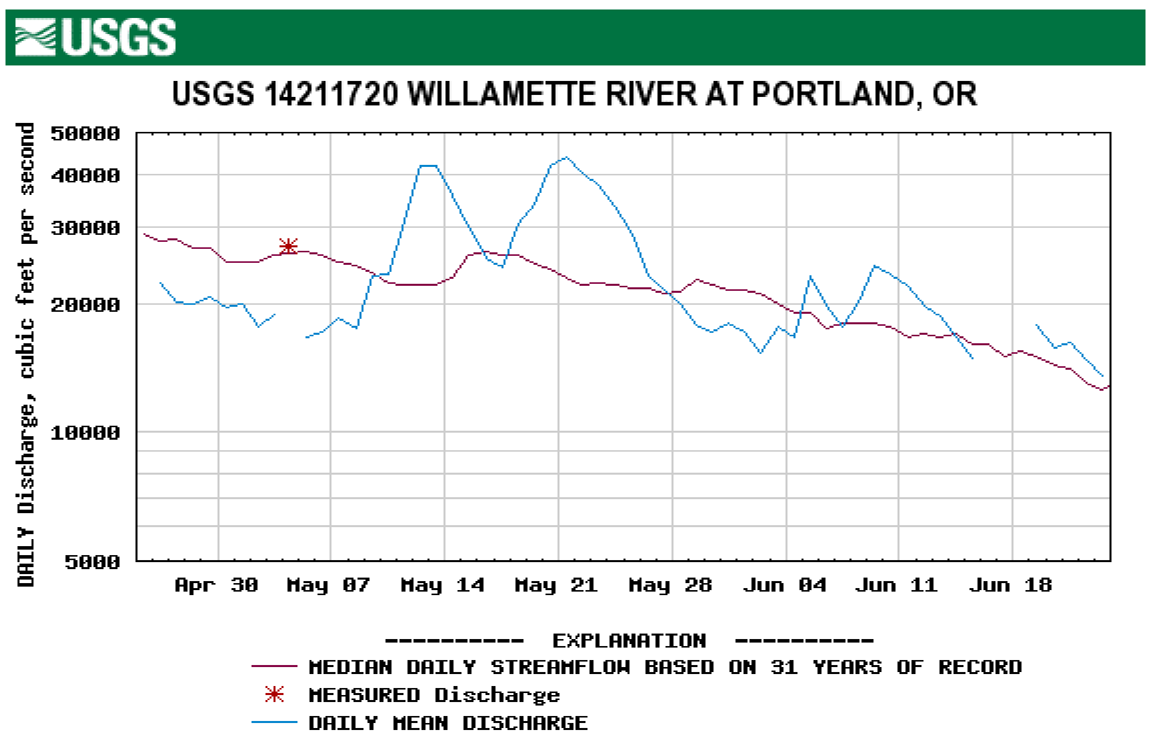


Figure 1b: Daily Willamette River flow at Portland) in ft^3s^{-1}. The Willamette is a major source of iron to the Columbia River plume.

The Willamette is likely the primary source of Fe to the system, and the Snake has a relatively high sediment load, though this has been reduced by the four dams in the lower Snake River. The high N and Fe levels seen in estuarine waters by R/V Wecoma can likely be attributed to the influence of the Willamette. Because there are no storage reservoirs and only one dam on the mainstem of the Willamette, there is less opportunity for nutrients and particles to be stripped from the water column than in the mainstem Columbia, with its numerous reservoirs.

Winds during the cruise were quite variable. Although there was no period of prolonged upwelling, the first large scale map (29 May to 3 June) was accomplished under upwelling conditions, which did not, however, become fully developed. The period 4-15 June was one of shifting winds but westerly swell, indicating the presence of low pressure offshore. One storm (16-17 June) required a break in plume sampling, though we were able to accomplish estuarine sampling during this period. The final map (18-21 June) also occurred under conditions of variable winds.

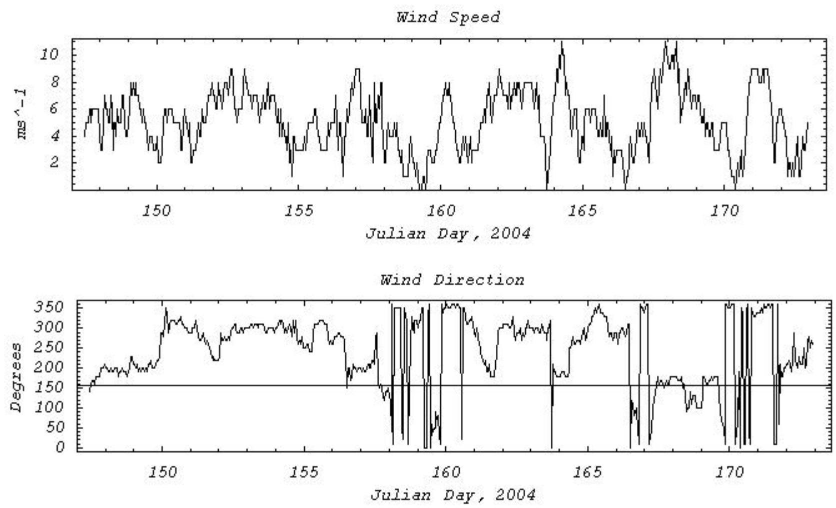


Figure 2: Winds observed during the cruise period at the NOAA MCR buoy 46029

Three RISE research groups carried out work on the R/V Pt Sur during Rise 2001:

1) The Jay group (David A. Jay, Jiayi Pan, Justin Broderson, Keith Leffler, Philip Orton, and Alex Brown, OGI/OH&SU) carried out Triaxus (Figure 3) surveys of the plume and studies internal waves, tides, vertical mixing, and fronts. The goals of this part of the project include describing the diverse physical processes occurring in the plume on scales (from vertical mixing to plume circulation), understanding the dynamics of internal waves, tides and fronts in the plume, and determining how these diverse, multi-scale processes contribute to productivity in the plume ecosystem Triaxus surveys characterize the plume-scale fields of near-surface velocity, salinity, temperature, nitrate, chlorophyll a, transmissivity, optical particle size and zooplankton characteristics. Large-scale maps were carried out under variable conditions at the beginning and end of the cruise. Frontal surveys were carried out during neap and spring tides, but primarily on spring tides. Observations of the plume lift-off zone were carried out with intermediate tidal forcing. Because of the lack of upwelling conditions, northerly fronts were not as strong as in 2004, but western fronts were very active in spawning internal waves.

2) The Peterson group (Bill Peterson, Leah Feinberg, Tracy Shaw and Jay Peterson, NOAA): The goal of this part of the project is to investigate the distribution, abundance, and species composition of mesozooplankton in the Columbia River plume area. It uses a two-component approach to study the spatial variation of zooplankton species and life stages as well as their rates of growth, grazing, and mortality associated with the coastal regions impacted by the Columbia River plume. The first component focuses on rates and involves net sampling and live organism incubations aboard the R/V Wecoma (c.f. the R/V Wecoma cruise report). The second (Pt. Sur) component focuses on high resolution surveys of plankton distribution and size using a Laser Optical Plankton Counter (LOPC) incorporated into a Triaxus tow body operated by the Pt Sur (Figures 3a and 4). The LOPC gathered data on the abundance and distribution of particles between 100 um and 35mm in equivalent spherical diameter (ESD) throughout the region surveyed by the Triaxus (see cruise tracks below). Zooplankton size and abundance data is gathered real-time in association with GPS, salinity, temperature, depth and fluorescence data.

3) The UW Civil and Environmental Engineering group (Alex Horner-Devine and Emily Spahn) conducted Triaxus surveys of the plume and frontal studies in coordination with the Jay group, but with an emphasis on particle properties deduced from the LISST-100, LISST-25 and bottle samples. The primary objective of this work is to measure the time-varying particle distribution in the near-field of the plume and identify mechanisms that lead to this observed distribution. The observed spatial and temporal variability will be compared with variability in other measured plume parameters such as micronutrient concentration and productivity in order to determine the role that particles play in the plume-influenced coastal ecosystem. Another area of interest is the rate of growth of the initial plume bulge and the transition to a coastal flow on the downstream side.

RISE 2 Personnel

Name	**Institution**	**Position (chief scientist, student, technician, etc.)**	**Dates on Board**
David Jay	OGI/OHSU	Chief Scientist	29 May-21 June
Alex-Horner Devine	UW	Watch Chief	29 May-21 June
Philip Orton	Lamont Doherty	Watch Chief	29 May-21 June
Jiayi Pan	OGI/OHSU	Research Scientist	29 May-21 June
Jay Peterson	NOAA	Research Scientist	29 May-21 June
Justin Broderson	OGI/OHSU	Research Associate	29 May-21 June
Keith Leffler	OGI/OHSU	Graduate Student	29 May-21 June
Emily Spahn	UW	Graduate Student	29 May-21 June
Alex Brown	OGI/OHSU	High School ASE Intern	10-21 June

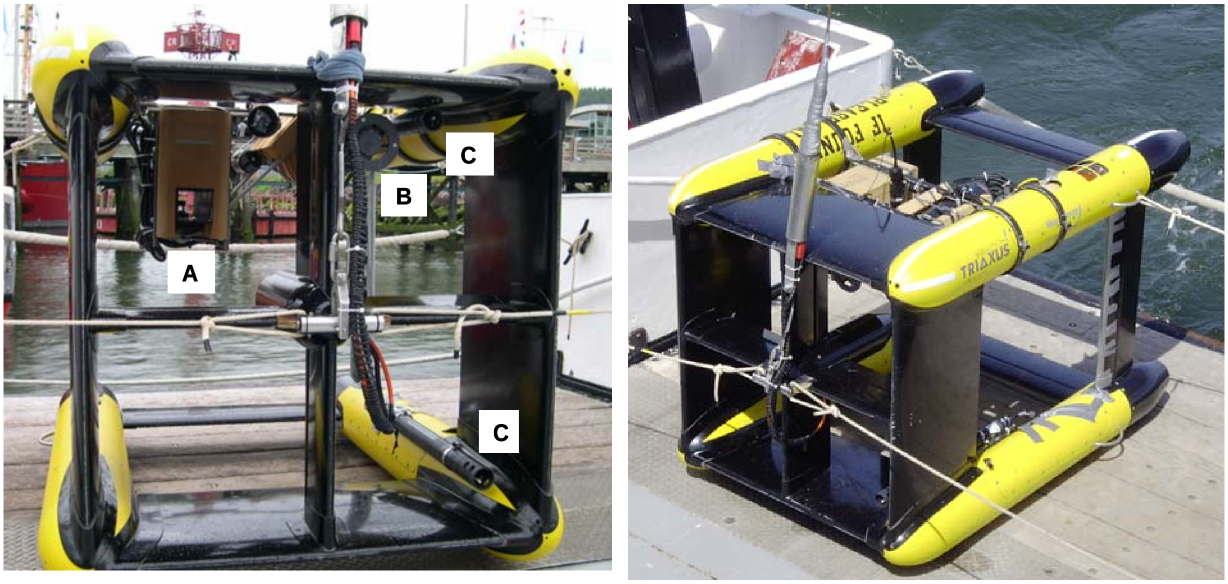


Figure 3a,b: At left in a), two views of the Triaxus towfish, showing the LOPC (A), LISST-100 (B) and the two OS-200 CTDs (C). The Remus-configuration 1200 kHz ADCP is mounted in the top right pontoon and looks upward; it is visible at right in b).

Figure 3c,d: At left in c) a close-up of ADCP head. At right in d) the pole-mounted Remus 1200 kHz ADCP (shown with pole retracted for transport). The first bin of good data is at 3.7 m nominal depth.

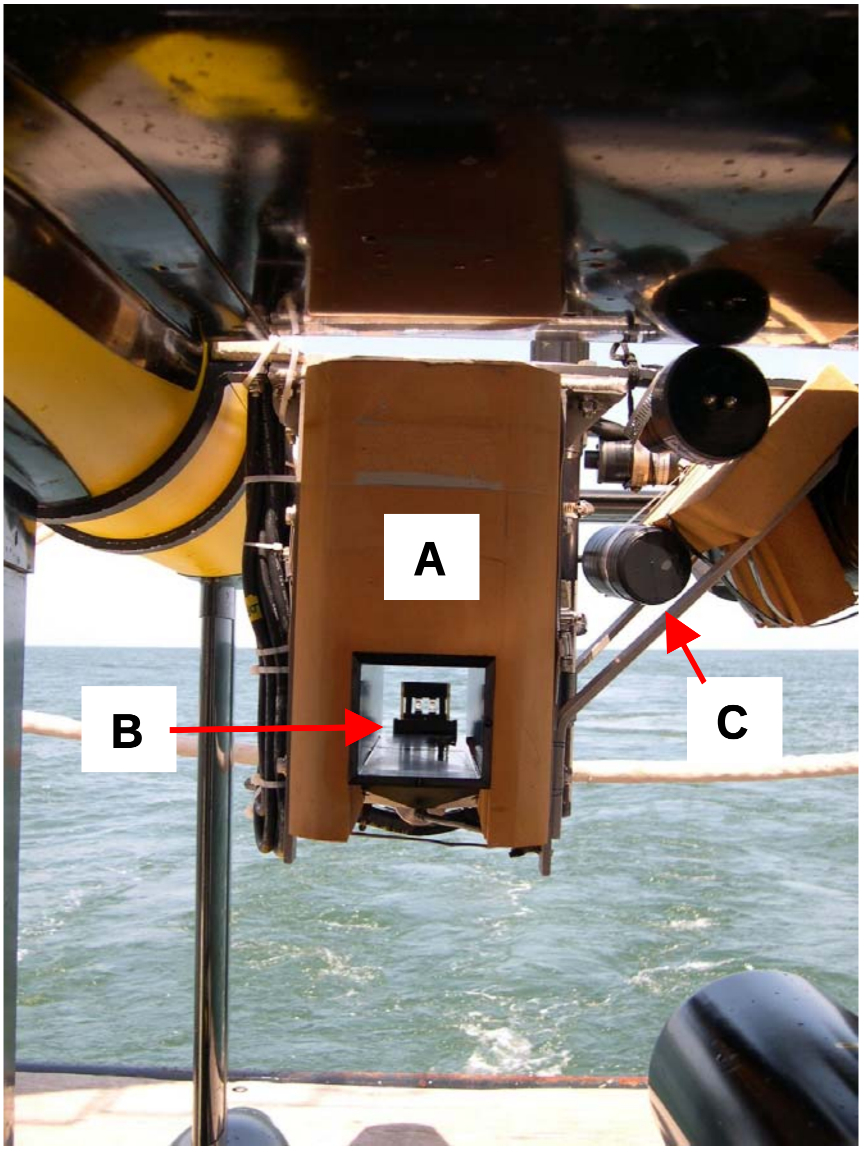


Figure 4: Detail of the LOPC as mounted on Triaxus: (A) with its attached conductivity, temperature, depth sensor ((B), mounted at the rear of the LOPC sampling tunnel) and fluorometer calibrated for chlorophyll a (C).

RISE 2 Itinerary

Date/Time, PDT	Pt Sur Sampling
	Staging in Newport
5/27 0800-5/29 1130	Stage in Newport
	Begin Cruise
5/29 1230 to 5/29 1730 (5 hrs)	Depart from Newport to sea, 40 m depth, 44° 38N, 124° 6W; do boat drill, lower ADCP pole; do plankton tow and CTD cast; bottles for N and SPM; put in Triaxus and test sensor/software function.
Map 1	**Map 1: Initial large-scale Triaxus map (see figure)**
5/29 ~1730 to 6/2 0300	Initial large scale map of plume under mixed upwelling/downwelling conditions and NW swell for most of map: > Triaxus E. on GH line E. to 40 m contour, 5/31 0500 to 5/30 1200 > Triaxus east along CM line, 6/1 0900 to 6/1 1800 Triaxus re-termination at outer end of GH Line, one other crab-pot by-catch
	Plume Axis Survey
6/2 0100 to 6/4 1200	Surveyed P-line with a zig-zag map from CM line (outer end) to CR buoy, with lines of 20-50 nm. Triaxus re-termination near CR buoy
	Inner Plume and Frontal Studies
6/4/1800 to 6/6 0000	Run NS line, catch two crab-pots and see remnants of strong N front
6/6 at 0000 to 6/6 1300	Attempted to survey N. front, but no sharp front found; weather change?
6/6 1300 to 6/7 0730	V-Map to north and attempt to survey EW line under rough conditions, which preclude normal frontal sampling. Sampling terminated after catching two crab pots
6/7 0730 to 6/9 0600	Survey S front near 46° 13 using NS-Line on mornings of 6/7 and 6/7. Survey full NS-line each night. Hit submerged object night of 6/7; Triaxus down for 6 hrs
	Drifter Studies
6/8 0600 to 6/9 2200	Pt Sur follows a drifter released by Wecoma, steaming in 6-20 nm lines, mostly along 46° 20N.
6/9 2200 to 6/10 1000	Coastal current line and NS line, partly with UDAS and ADCP only, because severed cable blows Triaxus power supply
	Personnel Change in Astoria
6/10 1000 to 6/11 0800	Personnel change in Astoria
	Studies of Plume Lift-off Zone
6/10 1000 to 1900	Rig CTD for towing and do experimental tows out and back across bar at 3 kn. Triaxus not used due to severe bar conditions
6/11 000 to 6/12 2200	Series of five tows back and forth across bar, ending outside
	Inner Plume and Frontal Studies
6/12 2200 to 6/14 daybreak	Sample on 46° 13.31N Line, including sampling of western front; catch one crab-pot

6/14 0600 to 6/15 1800	NS-Line. Just as we were about to start sampling fronts on 46° 13.31N Line, Triaxus termination breaks. Traxus back in at 1400. At 1800, CTD, net-two and pull pole to transit to Astoria ahead of storm
	Estuarine Sampling
6/15 2200 to 6/18 0400	Break for bad weather in Astoria
6/17 0800 to 6/17 1700	Sample line of stations down South Channel with CTD, LISST-25 and bottles, for calibration of LISST and ISUS N-sensor
	Final Map
6/18 0400 to 6/20 1300	Final map under post-storm conditions. Do inshore CTD line on night of 18-19 June from Grays Harbor south to MCR. Map extends from Grays Harbor to Newport, finishing on the Newport line. At 0600 20 June, Triaxus had to be re-terminated, ending sampling of Newport line except UDAS
	END OF CRUISE

List of Sensors/Data Sets Acquired

Shipboard:

1) Vessel 300 kHz RDI acoustic Doppler current profiler (ADCP), downward looking: profiles of horizontal velocity.
2) Pole-mounted 1200 kHz RDI (Remus) ADCP with Mode 12 firmware, downward looking: profiles of horizontal velocity.
3) Pole mounted OS-200 CTD: conductivity, temperature and depth at 1 m nominal depth.
4) Underway data acquisition system (UDAS), Seabird 911 CTD with transmissometer and fluorometer: conductivity, temperature, optical transmission, and chlorophyll a at 3 m nominal depth.
5) CTD casts:
    a. Seabird 911 CTD with transmissometer and fluorometer; conductivity, temperature, depth, optical transmission, and chlorophyll a.
    b. Laser in-situ scattering transmissometer, LISST-25; volume concentration in two size bins, 3-62.5 and 62.5 to 500 micron.
    c. Bottle samples for total SPM, nutrients, and chlorophyll a.

Triaxus Tow Fish:

1) Seabird 911 CTD with transmissometer, fluorometer, ISUS NO_3 sensor; conductivity, temperature, depth, optical transmission, chlorophyll a, and $N0_3$.
2) 1200 kHz RDI (Remus) ADCP with Mode 12 firmware, upward looking; high resolution, near-surface horizontal velocity profiles
3) Laser-optical plankton counter (LOPC); abundance and distribution of particles between 100 µm and 35mm in equivalent spherical diameter (ESD).

4) LISST-100; volume concentration in 32 size bins, 10-1,500 micron
5) Two OS-200 CTDs; conductivity temperature and depth (for stratification and vertical mixing from fine structure).

Selected Results

1. Regional-Scale Plume Maps:

RISE uses regional-scale maps to capture the plume in its coastal upwelling ecosystem setting, usually twice during a cruise. This regional mapping provides a context for process studies. Regional maps were executed at the beginning (29 May to 2 June 2005) and end (18 to 20 June 2005) of RISE 2 using both vessels. Pt Sur towed Triaxus in a boustrophedonic or zig-zag pattern, while the Wecoma focused their efforts on lines at Grays Harbor, Cape Meares and along the plume axis.

Map 1 (29 May to 2 June 2005) surface salinity and chlorophyll a (Chl) from the Pt Sur UDAS (underway data acquisition system) are shown in Figure 5a. Although winds were variable and little or no upwelling was occurring, the plume moved south. Note the association of Chl with plume waters. The Wecoma observed relatively high N, iron and Si levels (originating from the Willamette and coastal rivers) in estuarine waters, and these nutrients were then used up in the stable plume environment. In the absence of upwelling, plume waters provided the primary source of nutrients during this period. The plume was also more turbid than surrounding waters. Figure 5b,c shows salinity and other properties observed by the Triaxus Seabird CTD along a section across the plume. Plume waters ($S<\sim27$) are characterized by high Chl and some remaining N. Shelf water show high sub-surface N that was probably not available for immediate utilization.

Map 2 (18 to 20 June 2005) surface salinity and Chl from the Pt Sur UDAS are shown in Figure 6a. This map was taken just after a storm (16-17 June) than pushed plume waters onshore. A split plume configuration is seen, with low-salinity waters both south and north of the Columbia River, but most of the plume is north of the river mouth. As in Map 1, the highest Chl levels are seen in plume waters. Winds were initially light during this map, but became upwelling favorable on 19 June. Figures 6b,c show output parameters from the Triaxus Seabird CTD. In this case, N levels are low in plume waters, and subsurface waters show higher N levels than in Figure 5b. High Chl levels are seen in the lowest salinity plume waters. It is unclear whether this is related to mixing in the inner plume, or to remnant chl from estuarine productivity.

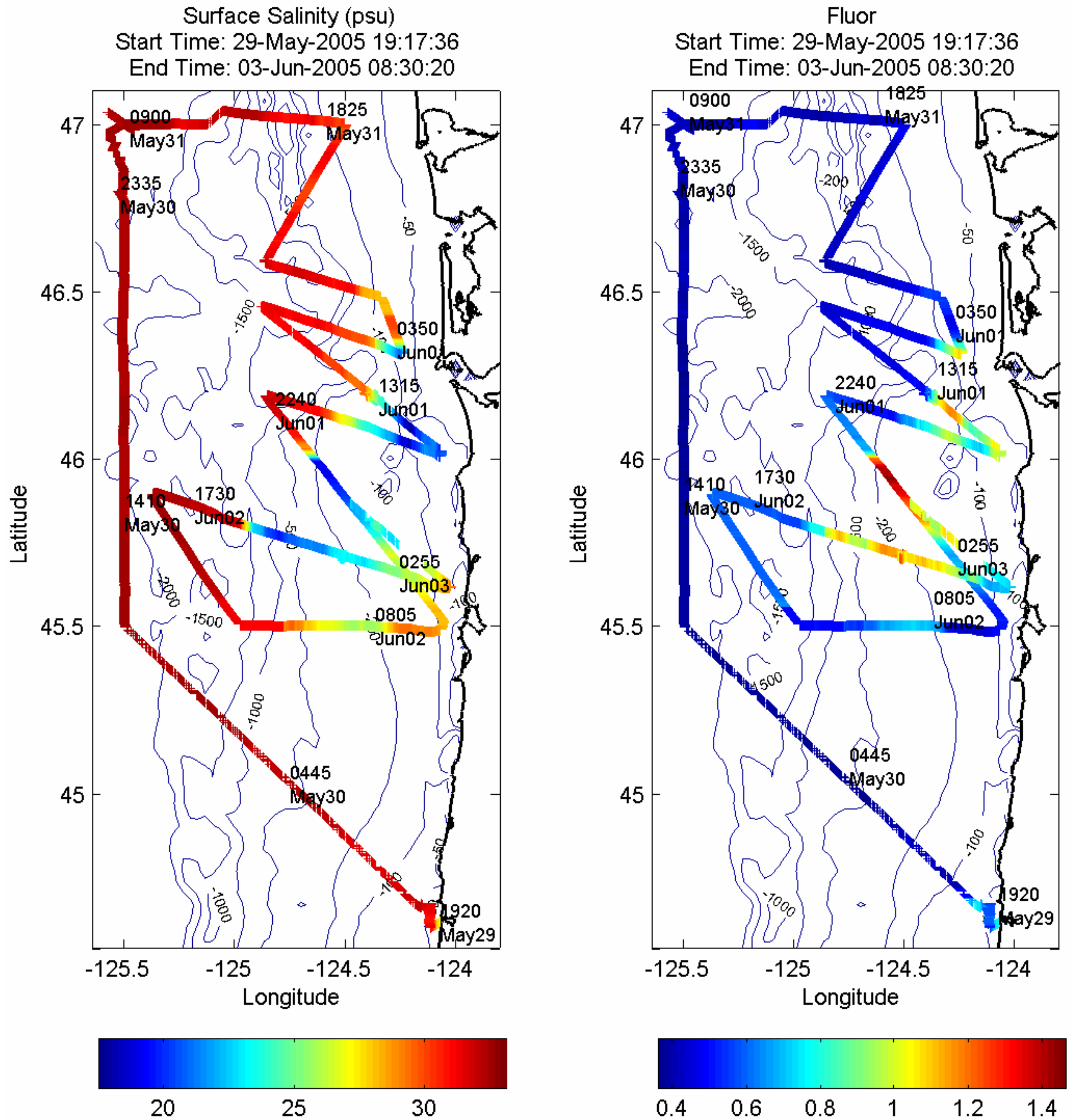
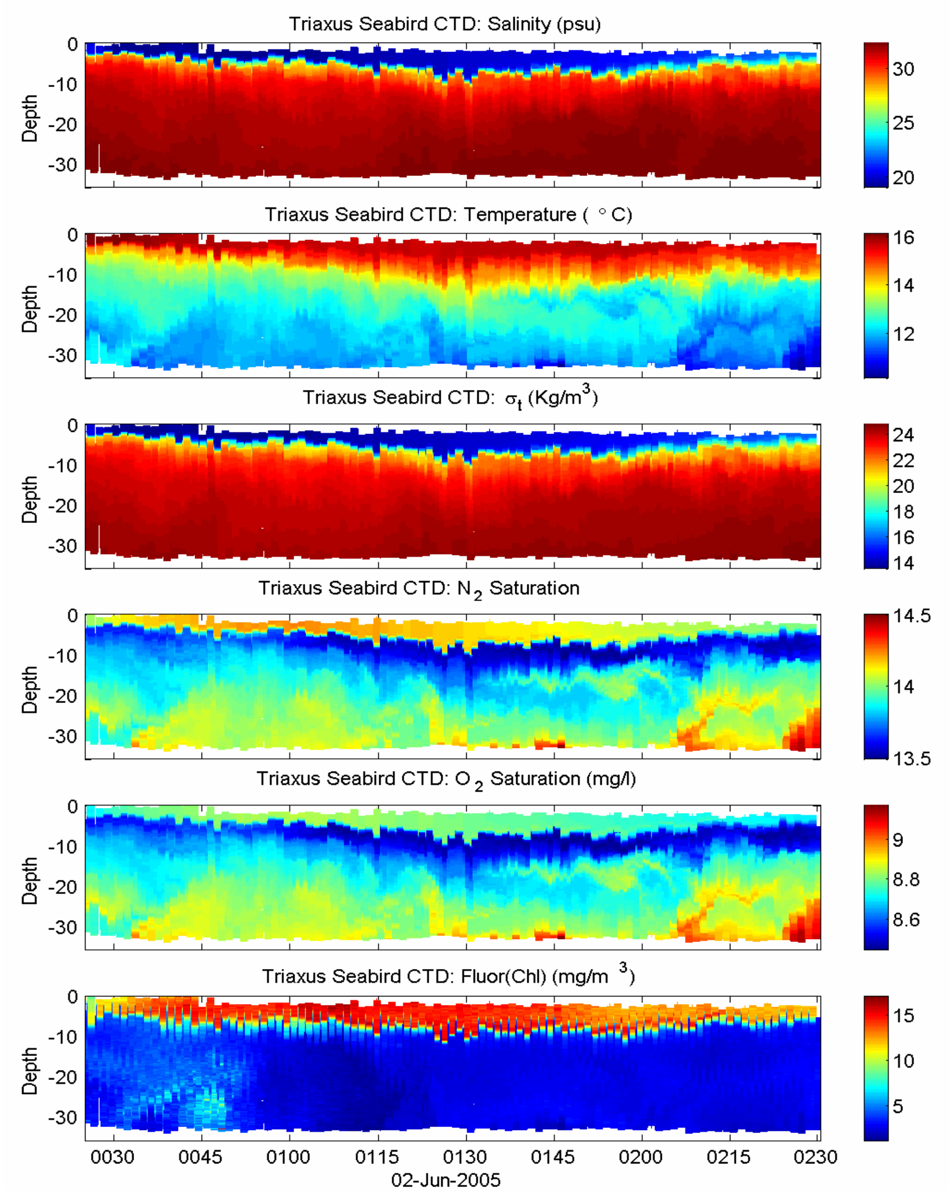
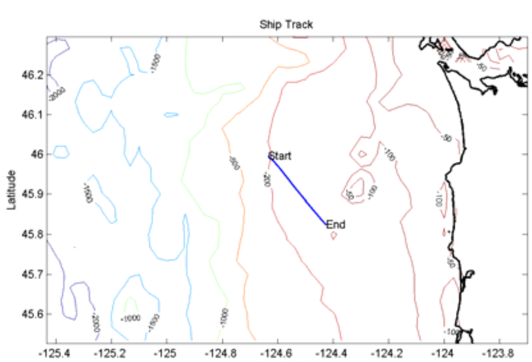


Figure 5a: UDAS surface salinity (left) and fluorometer chlorophyll a (right, arbitrary units) from plume Map 1. The low-salinity water is primarily to the south of the source, the Columbia River mouth. Chlorophyll levels are elevated in the plume. No evidence of upwelling is seen.



b)

Figure 5b: Plume cross-section from Map 1 showing output variables from the Seabird sensors on-board the Triaxus; N units are arbitrary, pending calibration.



c)

Figure 5c: The track position for the transect in 5b.

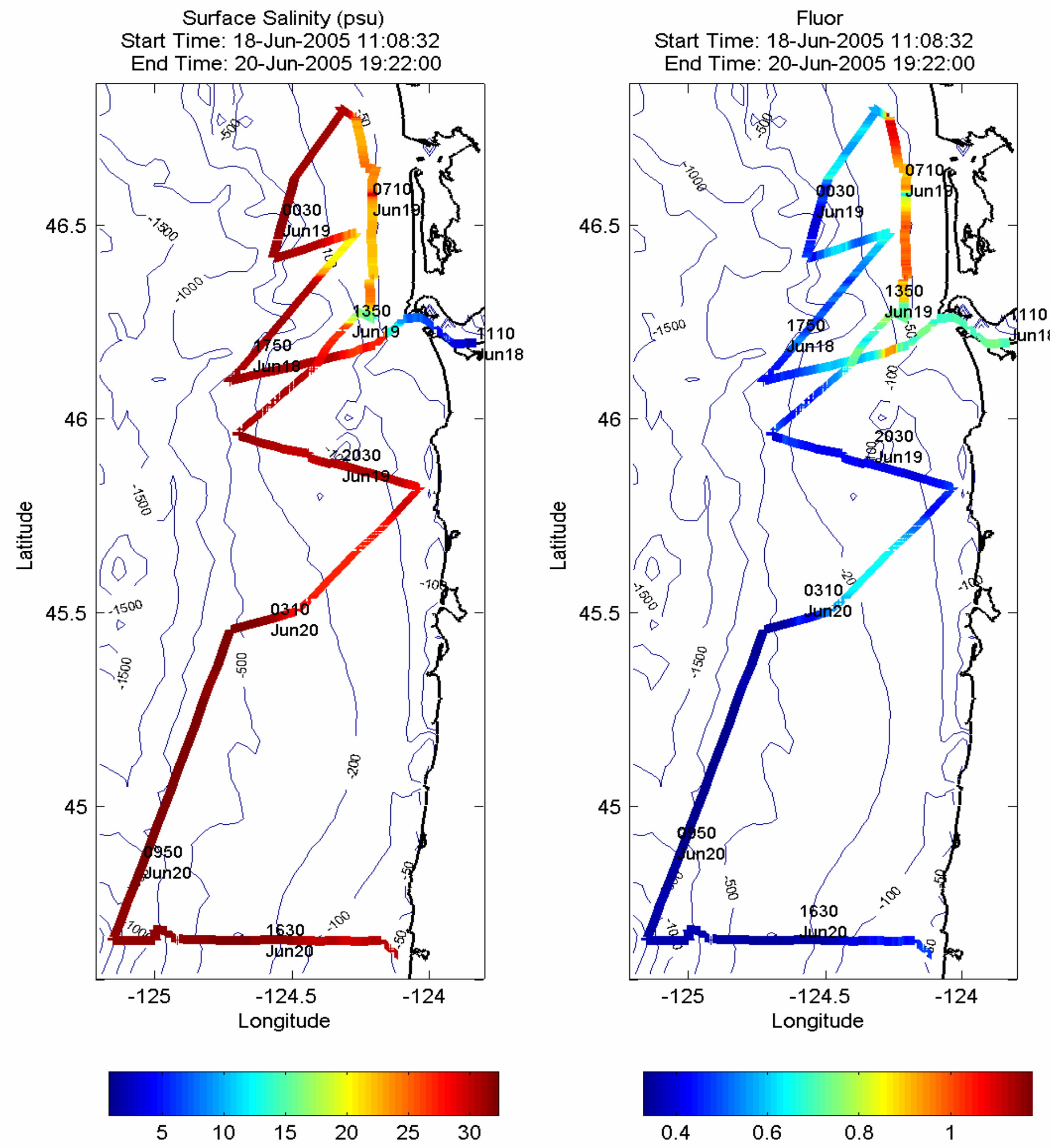


Figure 6a: UDAS surface salinity (left) and fluorometer chlorophyll a (right, arbitrary units) from plume Map 2. The plume is primarily to north of the source at the Columbia River mouth. Chlorophyll levels are again elevated in the plume, but lower than in Map 1.

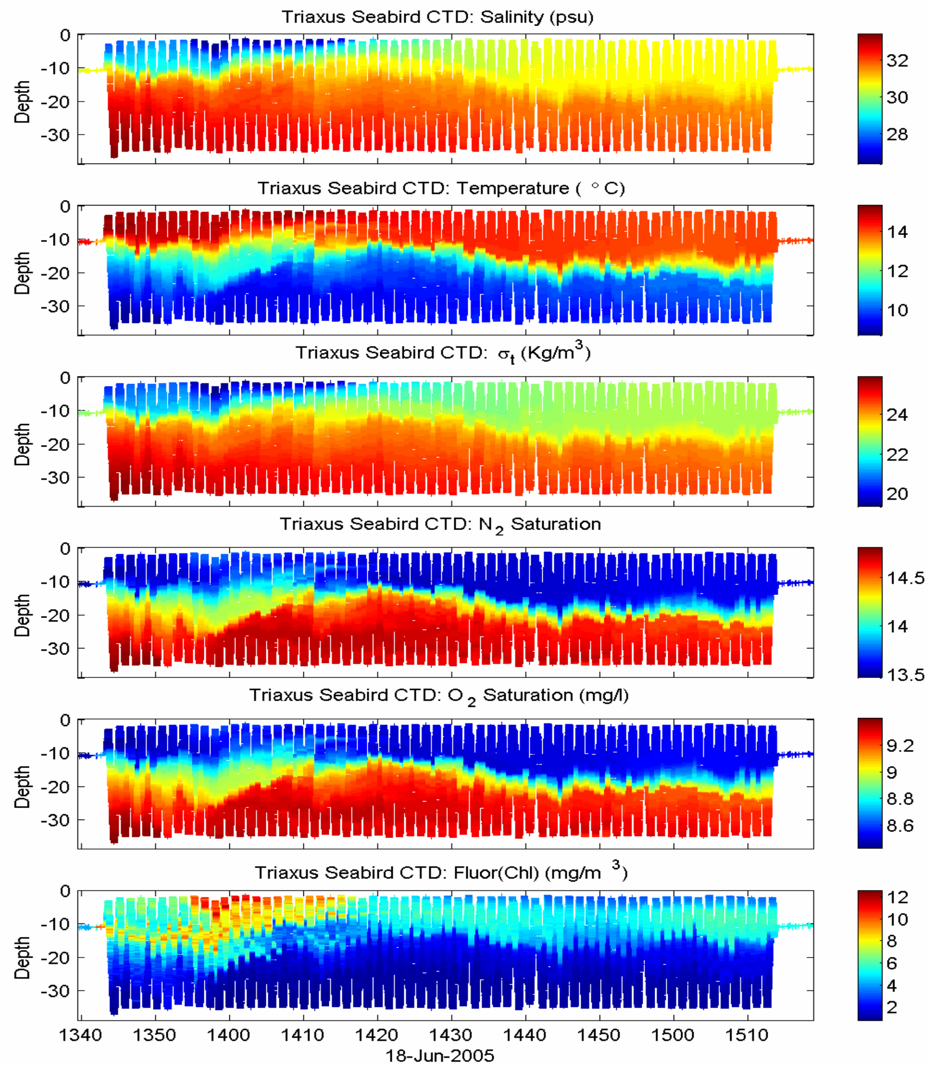


Figure 6b: Plume cross-section from Map 1 showing output variables from the Seabird sensors on-board the Triaxus; N units are arbitrary.

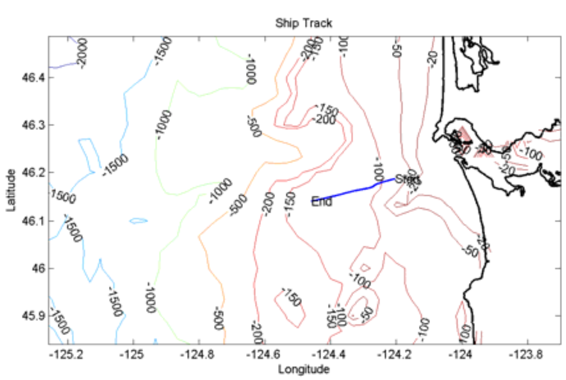


Figure 6c: The track position for the transect in 6b.

2. Frontal Processes

Fronts are an important plume environment, and a variety of fronts were observed in the plume area. These fronts accumulate particles and organisms, may exhibit high vertical mixing rates, and support feeding by seabirds and juvenile salmonids. Strong tidal currents and buoyancy input sometimes cause these fronts to exhibit large density contrasts ($\Delta S > 20$ over <150 m), sharp convergence ($\Delta U > 0.5\ ms^{-1}$ over <150 m), and rapid propagation (sometimes in excess of 1 ms^{-1}). Such fronts provide a productive habitat where zooplankton, birds and juvenile salmonids congregate. Frontal mixing also assists in maintaining plume productivity despite high ambient stratification (Orton and Jay, 2005). Frontal types include:

a. V-shaped salinity intrusion fronts inside the estuary mouth on flood.

b. Lateral fronts bounding the estuarine outflow; these are especially prominent on greater ebbs and cause considerable mixing (e.g., Figure 7).

c. Northern fronts propagating into high salinity water, relatively weakly stratified waters. These fronts exhibit very strong convergence, especially when they propagate against ambient coastal flow that is to the south under upwelling conditions. Accordingly, these were found to be stronger in 2004 than in 2005. These fronts cause very strong mixing (Orton and Jay, 2005) and may spawn soliton trains (Nash and Moum, 2005), if there is sufficient stratification in the ambient ocean waters.

d. Southern fronts propagating into stratified, old plume waters with salinities considerably below ambient surface ocean levels. These were found to be very diffuse in 2004 when ambient coastal flow was to the south. They were somewhat sharper this year, when coastal flows were weak or inconsistent, but convergence remained modest, as in 2004.

e. Western and northwestern plume fronts propagating into old plume waters with salinities considerably below ambient surface ocean levels. During RISE 2, these fronts seemed to be more successful in spawning soliton trains than either northern or southern fronts, possibly because they propagated with relatively high energy levels into stratified waters (Figures 8-10).

3. Internal Waves

High ambient plume stratification and strong currents, coupled with coastal topography, provide an environment that is exceptionally rich in internal waves and soliton trains. These internal waves play an important role in plume mixing and may also transport organisms and particles. At least one type of these is directly related to frontal propagation, as observed during RISE 1 in 2004 (Nash and Moum, 2005) and as described in the previous paragraph. Nash and Moum show that soliton trains are spawned when the speed of frontal propagation drops below the intrinsic propagation speed of internal waves in the coastal ocean outside the front. We observed further examples of this phenomenon during RISE 2 (Figures 8-11). These waves do not, however, form in association with all strong plume fronts, the number of waves formed is highly variable from day to day, different parts of a single front will form variable numbers of waves, and some frontal segments may not release any solitons. Clearly, there is much to understand about these waves.

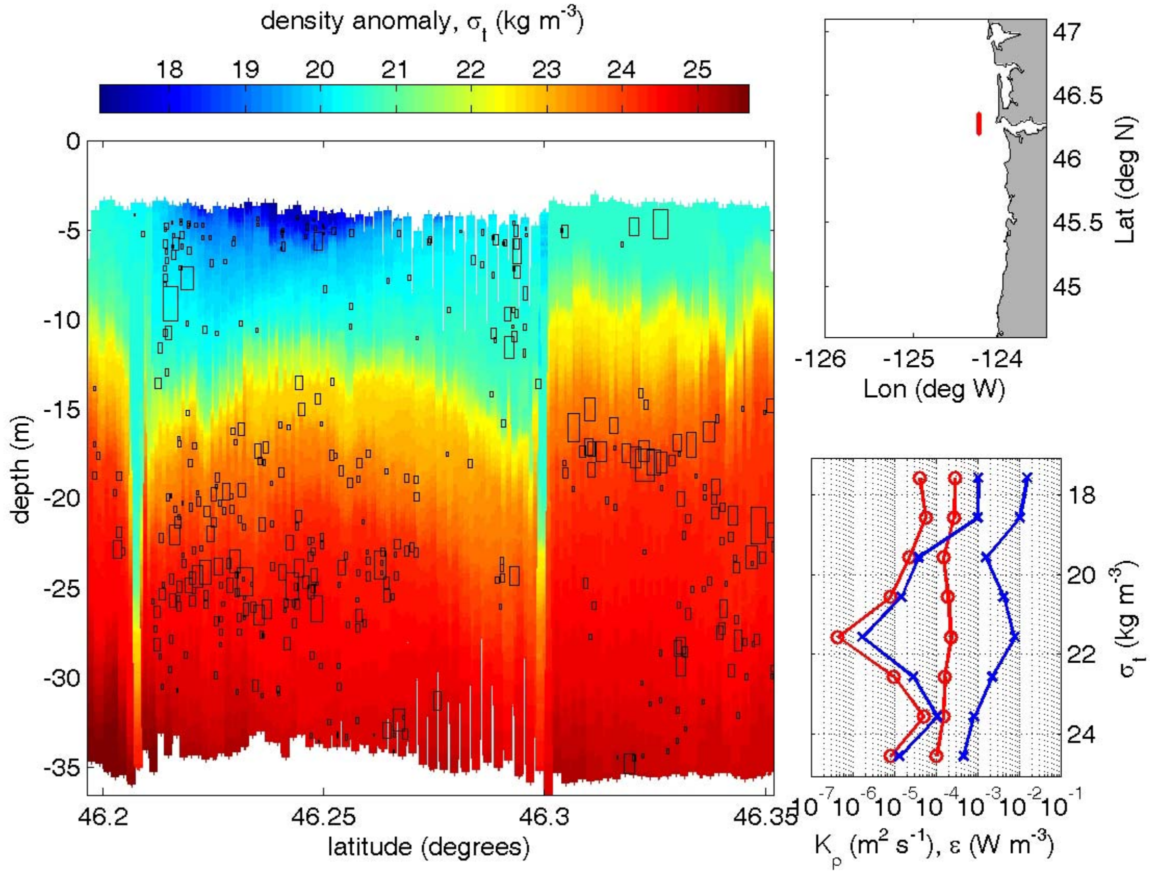


Figure 7: At left, a mixing summary diagram for the period 06/05/05 12:19 - 13:57 h UTC (5-7 h past HHW) shows a density section, with superimposed overturn patches as rectangles. The left side of the rectangle marks the location of the patch in terms of the x-axis. The height of the patch represents the height for the patch, following the depth scale to the left. The width of the patch represents the Thorpe scale for the patch, also following the y-axis scaling. Regions without boxes are not necessarily lacking overturns; these regions may have failed the quality control tests or may have overturns with a size or density offset below the sensor resolution. At top right, transect location. At bottom right, floor and ceiling values for transect-mean eddy diffusivity (blue) and turbulent kinetic energy dissipation (red), both bin-averaged over the transect in terms of density.

Figure 8 shows the surface expression of a train of solitons spawned at a northwestern front on the afternoon of 8 June on a spring tide. A SAR image of similar solitons generated from plume fronts is shown in Figure 9, but for 3 June 2005. The ship radar images in Figure 10a,b were taken a few minutes after the photo in Figure 8. The density and acoustic backscatter sections in Figure 11a captures the fission of the first soliton to leave the western front on 13 June(moderate tides), whereas Figure 11b captures a later stage of evolution of the train, about 2 hours after Figure 11a. Figure 11c documents for a transect from 13 June 2005 the mixing associated with the plume front and associated solitons.

Figure 8: The surface expression of a newly-spawned internal soliton spawned from a northwestern plume front, 8 June 2005; view is from the plume front side toward the ambient ocean. Two solitons spawned earlier are visible behind the first wave; the solitons are !150 m apart.

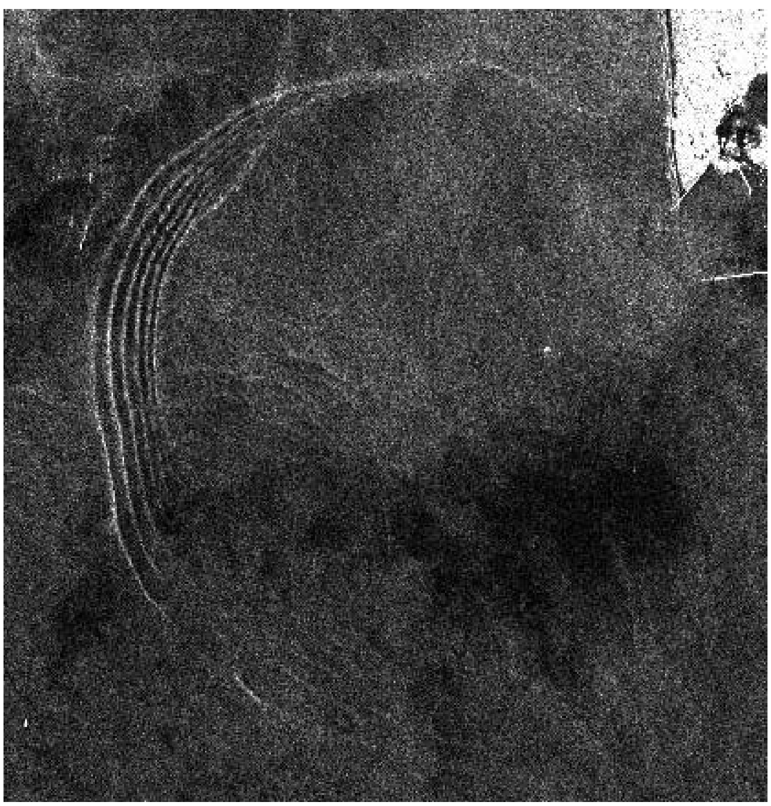


Figure 9: SAR image from 3 June. Although not taken on the same day as Figure 8, the solitons shown in this image represent the same phenomenon, but captured at a later stage in soliton evolution, when the wave crests are farther apart (~1km here vs. 150 m in the radar images below).

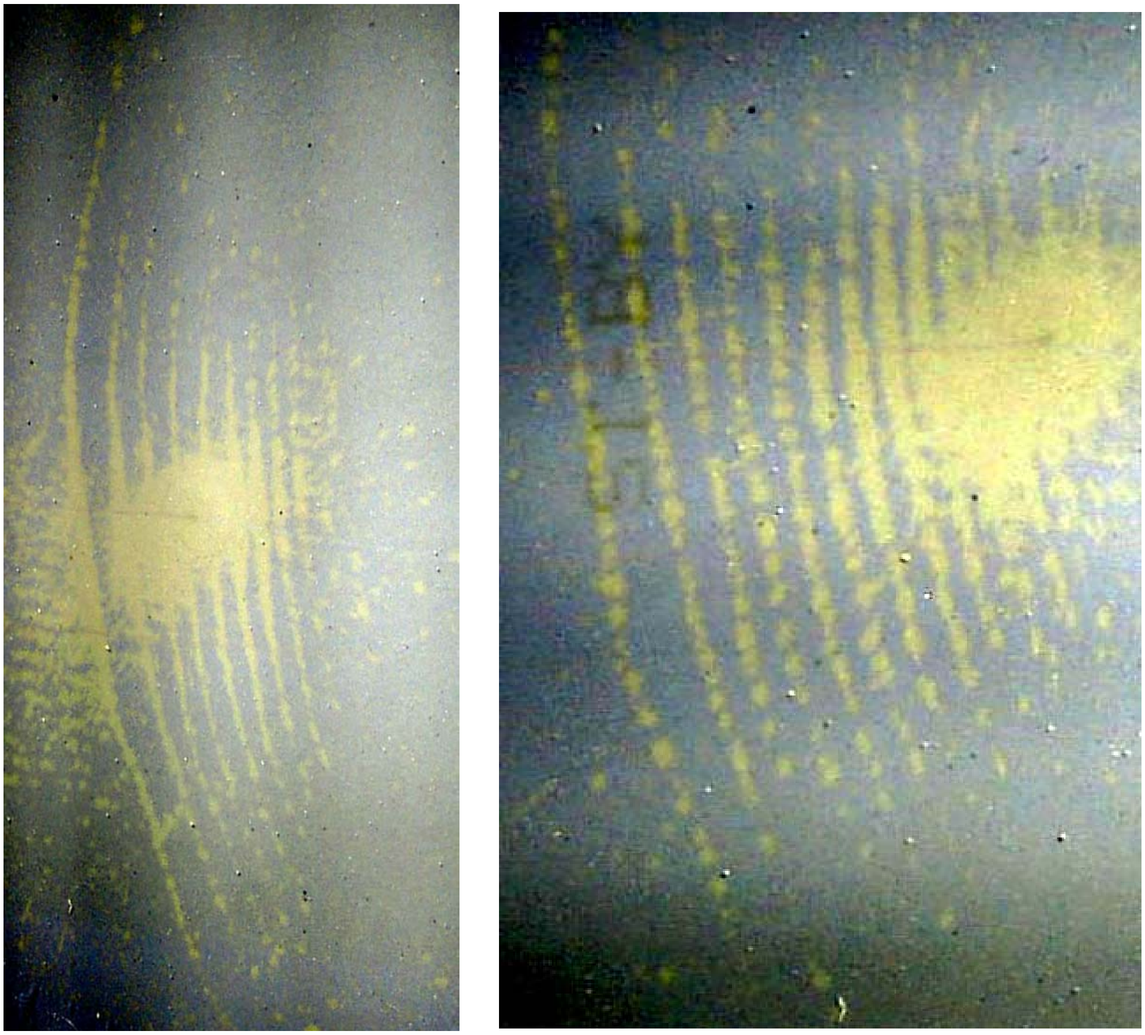


Figure 10a,b: A group of solitons propagating WNW (to the left) from a northwestern plume front (which is off the right-hand side of the image), as captured by the vessel radar on June 8. The radar shows first 9-10 solitons (at left) over a distance of ~2 km and then 14-15 solitons over ~3 km (at right).

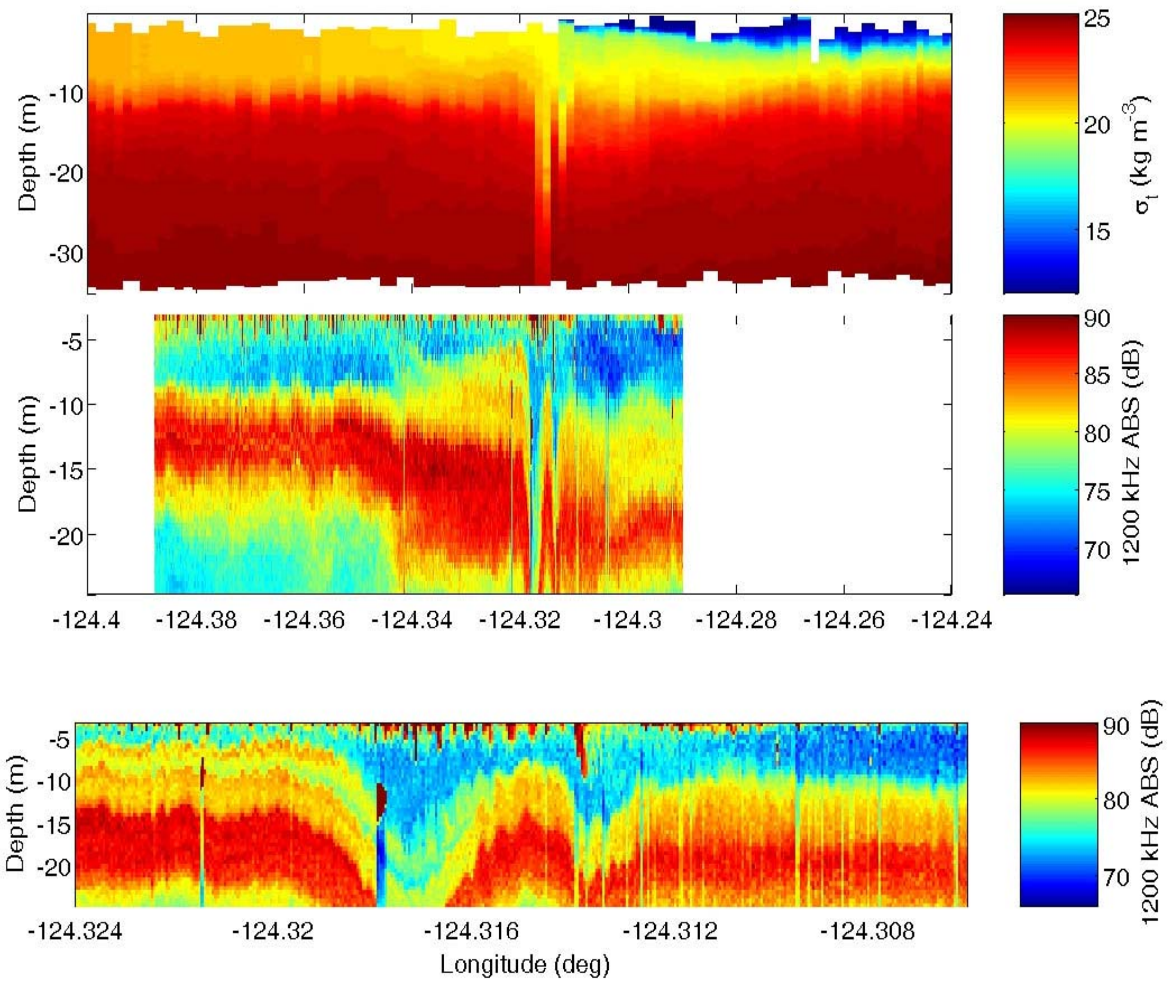


Figure 11a: Triaxus sigma-t section (top), single-ping 1200 kHz ADCP acoustic backscatter image of soliton fission from the northwestern plume front (middle), and detail from the acoustic backscatter section (bottom); note the difference in the horizontal scale at bottom. The double depression at -124.314 to 124.318 represents the front itself to the right and the newly spawned soliton to the left of the front. Note that the soliton is actually more energetic than the front in terms of vertical motion. The acoustic image provide a higher resolution than the Triaxus salinity data (ca. 1 Hz ADCP sampling vs. a 30-40 s Triaxus cycle time).

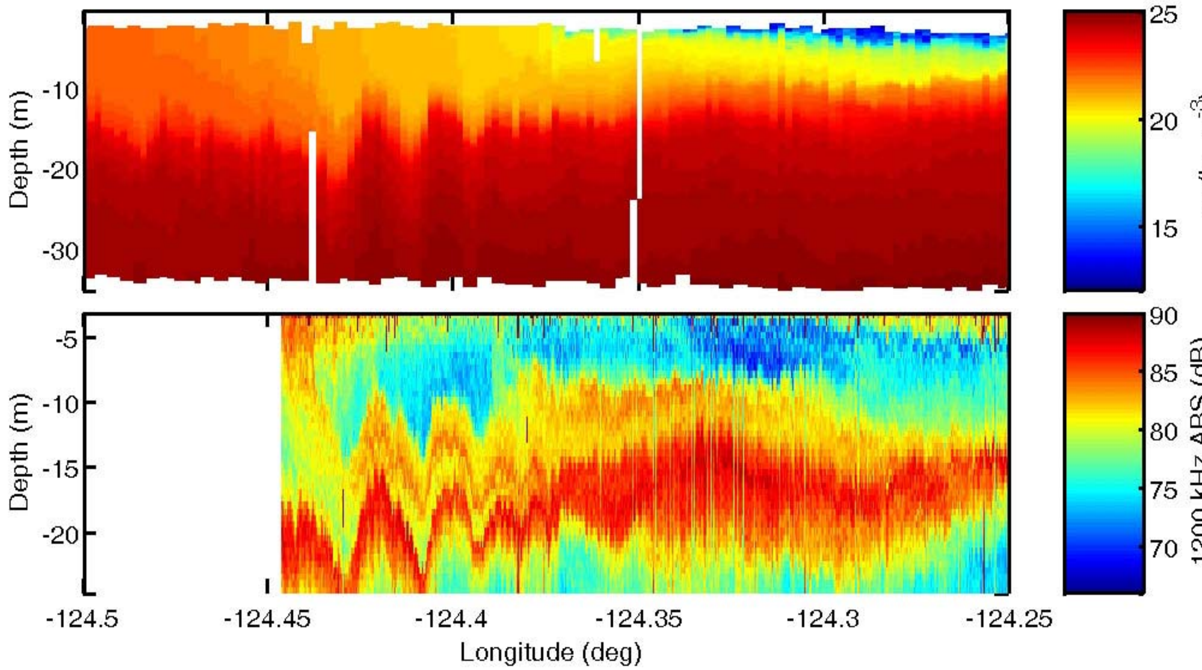


Figure 11b: Triaxus sigma-t section (top) and 1200 kHz ADCP acoustic backscatter image of soliton movement away from the northwestern plume front (below). This captures a later stage in evolution of the soliton train than Figure 11a. Note the presence of low salinity water beyond the plume front; this is apparently advected by the soliton itself.

The Nash and Moum analysis, our observations, and examination of SAR images assembled over the last several years suggest the following interpretation regarding the occurrence of these waves. In order to form solitons, a front must be quite energetic (initially super-critical with respect to the internal Froude number), with strong convergence causing formation of a bore head. A weak, non-energetic front without a bore-head will lack the energy to release solitons. The stratification of the ambient ocean outside the plume front is also vital, however, and this is one reason that the plume region is so rich in these solitons. The ocean on the seaward side of the front must be stratified (but not too stratified) such that the soliton propagation speed is less than the initial plume propagation speed, but greater than the intrinsic (linear wave) propagation speed of the stratified coastal ocean. Furthermore, soliton formation modulates the strength and propagation of fronts. The strongest fronts on the north side of the front during upwelling conditions maintain rapid propagation for up to 10 hrs past high water and may not spawn solitons, because they are propagating into nearly unstratified, high-salinity upwelled water. The northwesterly to southerly portions of the same front may more frequently spawn solitons, because they usually propagate into more stratified waters (cf. Figure 9). Finally, these solitons both transport freshwater across the initial plume front and propagate energy that may cause mixing outside the immediate plume bulge. Thus, they are likely to play an important role in plume and regional productivity.

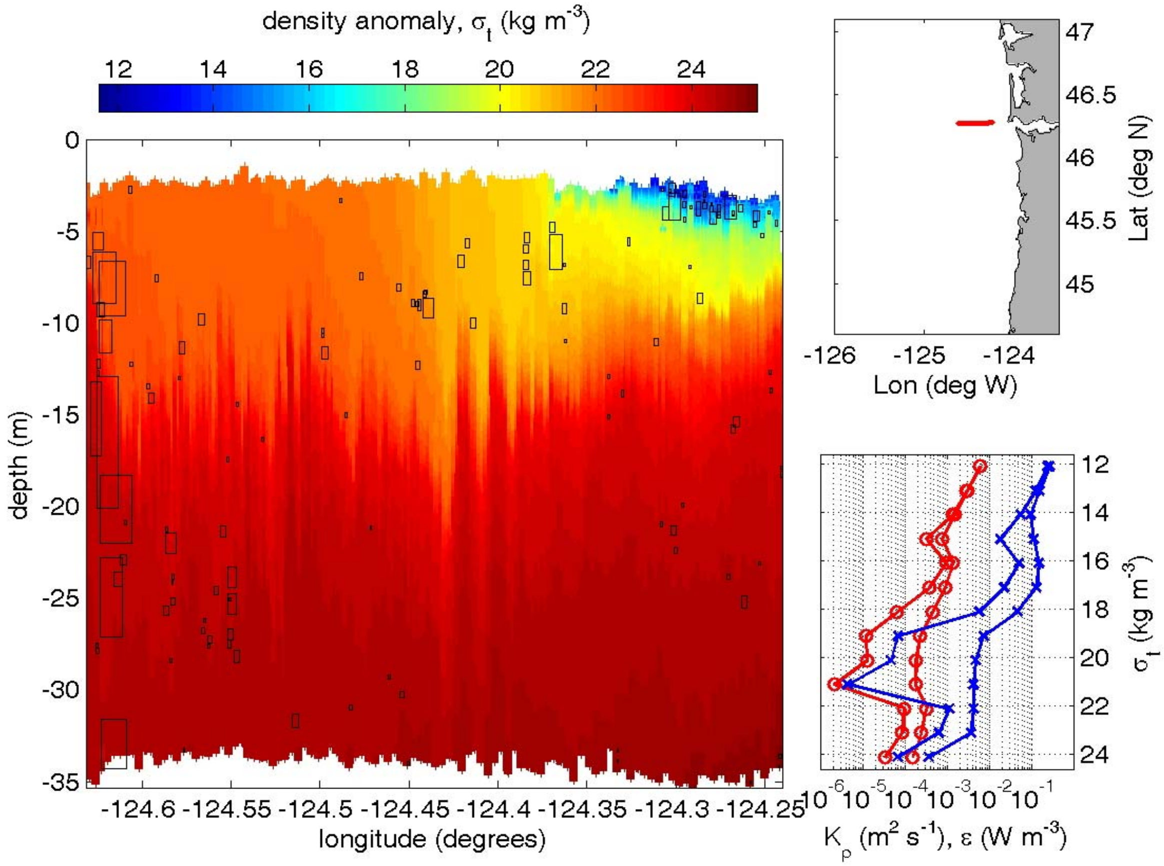


Figure 11c: At left, a mixing summary diagram across the plume front on the west side of the plume for 6/13/ 2005, showing a density section, with superimposed overturn patches as rectangles. The left side of the rectangle marks the location of the patch in terms of the x-axis. The height of the patch represents the height for the patch, following the depth scale to the left. The width of the patch represents the Thorpe scale for the patch, also following the y-axis scaling. Regions without boxes are not necessarily lacking overturns; these regions may have failed the quality control tests or may have overturns with a size or density offset below the sensor resolution. At top right, transect location. At bottom right, floor and ceiling values for transect-mean eddy diffusivity (red) and turbulent kinetic energy dissipation (blue), both bin-averaged over the transect in terms of density.

4. Vertical Mixing

Estimation of vertical turbulent mixing is vital to RISE, because vertical mixing is required to sustain productivity in the stratified waters of the plume region. The plume provides Si and Fe, but usually has little N – in this respect, Figure 6b is more typical than Figure 5b. The N and P needed for primary production are typically provided by upwelled waters. Mixing of plume and upwelled waters brings nutrients and micronutrients (N, P, Si and Fe) together in one water mass, making the plume region highly productive.

A fine-structure, turbulent length-scale analysis enables us to estimate mixing parameters in regions of energetic mixing using CTD density data. On Triaxus, we towed a SeaBird Electronics SBE-9 CTD and two horizontally mounted Ocean Sensors Model OS200 CTDs in a "tow-yo" saw tooth pattern, at horizontal and vertical speeds through water of about 3 m s^{-1} and 1 m s^{-1} respectively. The SBE9 sampling rate was 24 Hz, and the OS200 sampling rate was 9.1 Hz, though the actual sensor response times are similar. The OS200 has a rapid-response integral conductivity-temperature sensor, and was used successfully for detecting density fine-structure overturns in a recent study of Columbia River plume fronts (Orton and Jay, 2005). Here, we present only SBE-9 results, because the SBE-9 has a lower noise levels in density data, and the stratification is weaker than in our previous study. As expected from their relative noise levels, the OS200's typically detected the same overturns as the SBE-9 when they involved large density gradients but no overturns with small density gradients.

A Thorpe sort is used to restore each measured density vertical profile to a monotonic form, presumable representative of its mean state, unperturbed by transient turbulent eddies. The resulting statistics are used to estimate turbulence parameters. The process of sorting density yields a profile of L, the vertical distance over which each gravitationally unstable density data point has been moved. We compute the Thorpe scale L_T as the rms of L in each overturn patch. Strict quality control methods are used to avoid spurious overturns from measurement noise or from the horizontal movement of the towed platform (Orton and Jay, 2005; Ott et al., 2004). Overturn patches with rms density inversions less than the accuracy of the sensor are also eliminated.

Dissipation of turbulent kinetic energy is estimated as (Thorpe, 1977):

$$\varepsilon = a^2 \overline{L_t^2 \langle N^3 \rangle} \qquad (1)$$

Here, angle brackets denote an average over an overturning patch and the overbar an average over several profiles, and $a \approx 1$. Eddy diffusivity can be computed as (Peters and Johns, 2004):

$$K_\rho = a^2 \Gamma \overline{\langle N \rangle L_T^2} \qquad (2)$$

Here, the mixing efficiency is approximated as $\Gamma \approx 0.22$ for coastal stratified flows (Kay and Jay, 2003; Macdonald and Geyer, 2004).

Preliminary mixing estimates are presented as transect-averages, referenced to depth and density surfaces, with conservative floor and ceiling estimates. The floor is derived from averaging all data, including zeroes where no overturn was observed. The ceiling is derived from averaging all data, but substituting the minimum detectable value wherever no overturn was observed. Figures 7 and 11c provide examples of mixing estimates for a line across the estuary mouth on a strong ebb, along the NS-Line. Sampling lines are defined in Appendix B.

5. Plume-Scale Circulation

Definition of plume-scale circulation processes is vital to understanding cross-margin transport of particles and organisms, and Pacific Northwest regional oceanography. Laboratory and numerical model experiments have been extensively used to understand the circulation in river plumes. In these studies, out-flowing river water arcs to the right (in the northern hemisphere) until it returns to the coast. The recirculating current impinges on the coast and splits, diverting a fraction of the current back toward the river mouth and a fraction into a coastally trapped current that propagates away from the mouth. As a result of this bifurcation, buoyant water accumulates in the vicinity of the mouth and eventually forms a large, continuously growing eddy. This eddy, which rotates anticyclonically, is referred to as the plume bulge. According to most models, the bulge accumulates approximately half of the total river discharge and, therefore, significantly reduces the alongshore transport of river-borne matter such as sediment, nutrients, biota and contaminants.

An anticyclonic plume bulge has not often been documented in natural river plumes despite the fact that it is consistently observed in laboratory and numerical studies. There are a number of reasons for this. Primarily, factors not considered in models (e.g., tides, wind forcing, non-normal outflow angle, complex topography, a spatially variable coastal current and bottom friction) are significant in natural plumes and result in a more complex circulation than is seen in laboratory models. Also, mapping the circulation in river plumes is difficult due to the large length scales and short times scales that are inherent in these flows. The Triaxus sampling platform employed on the RISE cruise is capable of covering large distances within the plume in reasonably short periods of time. This presents a unique opportunity to map the circulation in the plume. The Columbia River inflow is characterized by Rossby and Froude numbers close to unity. This fact, in combination with the relatively steep shelf, results in a plume that is expected to form a clear bulge.

A bulge-like circulation was observed on a repeated north-south transect at longitude 124^o 20.0 W on 9 June 2005. This line is approximately 20 nautical miles from the river mouth and normal to the outflow direction (Figure 12a). The plume intercepts the line on the south end between 46^o15 and 46^o20 N. At this point the plume water is flowing south-west at approximately 0.6 ms^{-1} and is 10 m deep (Figures 12b-d). There is a strong flow to the east in the plume on the north end of the transect. At this point the maximum velocity is 0.4 ms^{-1} and the plume is only 7-8 m deep. The velocity structure observed in this transect is consistent with that presented in laboratory and numerical studies. In particular, both find that the onshore velocity varies linearly between the maximum offshore and maximum on-shore velocity (Figure 12c). In contrast, however, the density structure departs considerably from predicted patterns for steady plumes. Laboratory and numerical studies suggest that the bulge is in *gradient-wind* balance, and therefore that the bottom interface of the plume will be parabolic. This is not what is observed in the plume, however (Figure 12a). This discrepancy may be due to the unsteadiness of the forcing from the river, topography, or spatially variable along-shore flow.

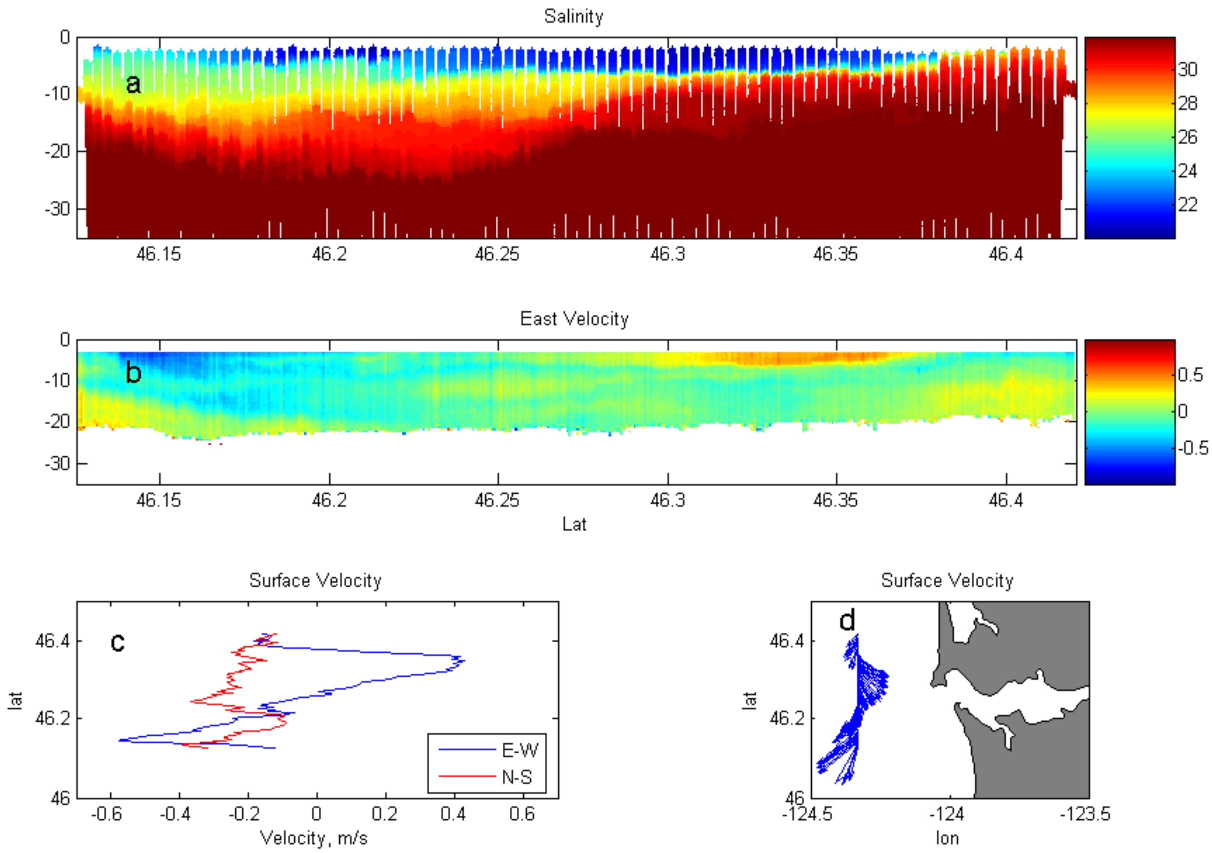


Figure 12: NS transect along 124° 20' W on 9 June: a) Salinity from the Seabird sensor aboard the Tri-axus Towfish. b) East-west velocity from a pole-mounted 1200 kHz ADCP on the boat. c) Profiles of East-west and north-south surface velocity taken from the pole-mounted ADCP. d) Feather plot of velocities from c) showing offshore flow opposite the river mouth and on-shore flow further north, consistent with the anticyclonic bulge circulation observed in laboratory and numerical plume experiments.

6. Plume Tidal Dynamics

Surface and internal tides play a major role in plume circulation patterns, frontogenesis and vertical mixing. Extraction of the tidal signal from shipboard observations is, however, a non-trivial process and will involve information from non-shipboard sensors (e.g., tide gauges, moored current meters and HF radar). Amongst the difficulties involved in tidal analysis of the velocity and salinity field in the plume area is the high mobility of the plume itself – tidal patterns may be totally different at a given location when the plume is present from when it is absent. Plume tides are, therefore, highly non-stationary and will require innovative data analysis methods. An idea of the complexity of plume tidal patterns can be seen from the ebb and flood velocity distributions across the NS-Line (Figure 13). The tidal currents are conspicuously non-reversing. The flood flow enters the estuary from the SW, whereas the ebb exits in a more westerly direction. Peak flood occurs at a more southerly location than peak ebb, and the flood is strongest below the surface.

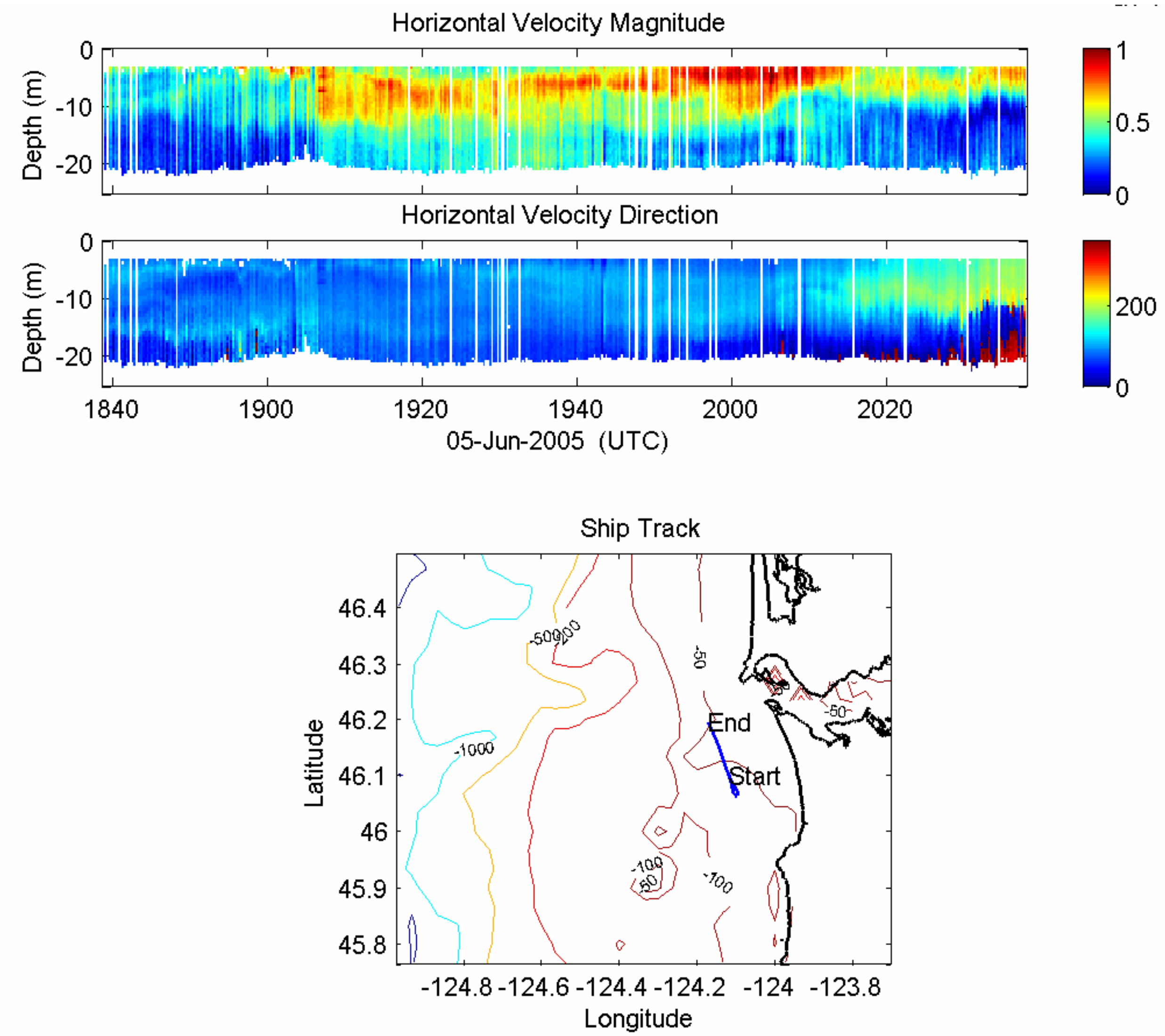


Figure 13a: Peak greater flood magnitude currents across the NS-Line on 5 June, as determined using the 1200 kHz, pole-mounted ADCP.

7. Plume Particle Dynamics

Several types of particles are found in the plume – particles may result from fluvial input of suspended sediment to the plume, from estuarine productivity, or in-situ biological processes. They may consist of inorganic material, living cells or detritus, or consiste of aggregates material from various sources. Particles in the plume may also be modified by aggregation and biological processes. Plume particulates are being studied optically. Figure 14 shows an example of output from the Laser In-Situ Scattering Transmissometer (LISST-100) on the Triaxus. The LISST measures volume concentration in 32 size bins from 10 to 1,500 μ. Ensemble number is on the x-axis (the LISST-100 samples at ~1 Hz), depth is on the y-axis, and the volume concentration of particles (sized between roughly 55 and 350 microns) is represented via color. The lines labeled A, B, C and D indicate crossings between river plume and ocean waters. At A (6/7/2005, 18:08 GMT), the ship passed through a visible plume front, going from river to ocean water, which

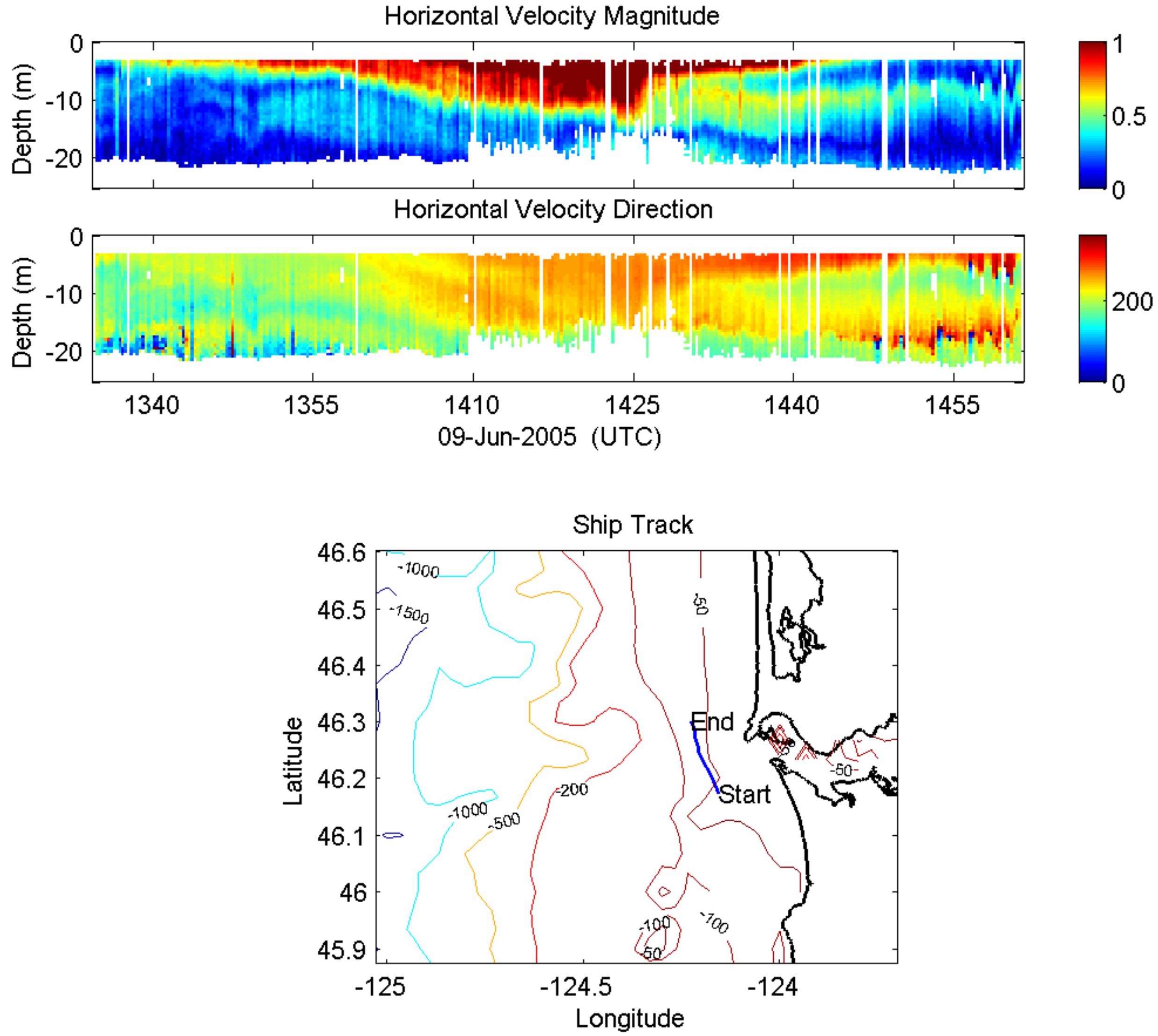


Figure 13a: Peak greater ebb magnitude currents across the NS-Line on 9 June, as determined using the 1200 kHz, pole-mounted ADCP.

coincided with the salinity rising from 17.8 to 23.5. At B (6/7/2005, 18:50 GMT), the surface salinity dropped from 28 to 15 as the ship passed back into fresher water. At C (6/7/2005, 19:08 GMT), we turned back into saltier water and the salinity rose more gradually than before, from 14.5 to 19.2. At D (6/7/2005, 19:46 GMT), we crossed the plume front again, heading into fresher water once more. Note that the front appears to weaken and dissipate over the time period represented here – the division between river plume and ocean waters is more stark at point A than at point D. There are also generally more particles in the river plume than in the ocean. Furthermore, particles in the area plume often exhibit sub-surface or sub-plume maxima, whereas particles outside the plume in ambient ocean water are concentrated closer to the surface.

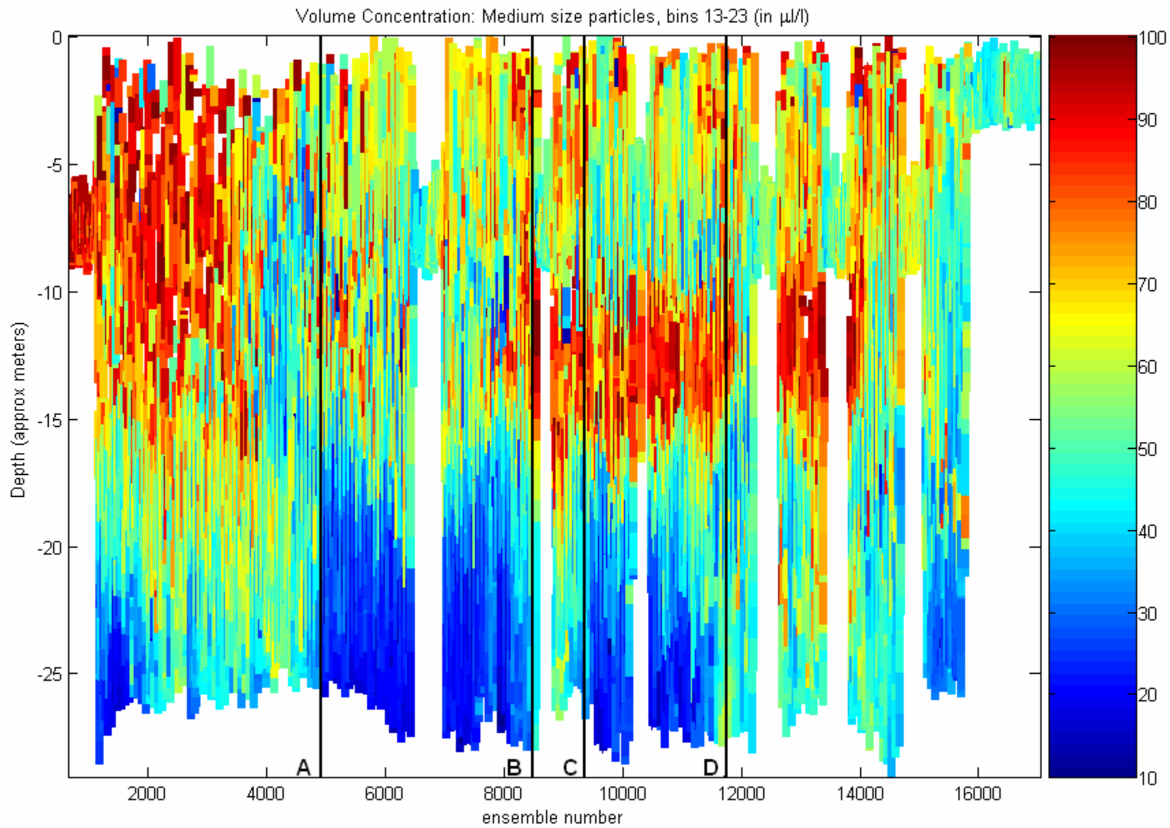


Figure 14: Volume concentration versus depth and ensemble number for medium-sized particles, from the LISST-100 mounted on the Triaxus.

8. Plankton Distribution

Zooplankton work carried out on the Pt Sur focused on high-resolution surveys of plankton distribution and size using a Laser Optical Plankton Counter (LOPC) mounted on the Triaxus. The LOPC gathers data on the abundance and distribution of particles between 100 µm and 35 mm in equivalent spherical diameter (ESD) throughout the region surveyed by the Triaxus. Zooplankton size and abundance data are gathered real-time in association with GPS, salinity, temperature, depth and fluorescence data. Vertical net tows (0.5m diameter net with 153 µm mesh) were periodically taken during the survey to collect zooplankton for species identification.

During the May 29 – June 20 cruise period, the LOPC collected over 3.4 GB of data during ~170 hours (7 days) of towing. The Triaxus undulated throughout the upper 30 – 100 m of the water column at a vertical velocity of 0.6-1.0 ms^{-1}, completing a full undulation every ~ 1 to 3 min, depending on tow depth and sampling protocol. The spatial sampling resolution was on the order of 180 – 500 m along-transect. LOPC data from the 46-16 Line off the mouth of the Columbia River (Figure 15) reveals strong interactions between the physical and biological fields along the frontal boundary of the river plume. These interactions are seen because the plume plays multiple roles in plankton dynamics. The plume is frequently a locus of high biomass and productivity. Also, plankton may accumulate on density interfaces associated with the plume.

Finally, an internal wave train propagating away from the river plume vertically displaces the concentrated layers of phytoplankton and zooplankton.

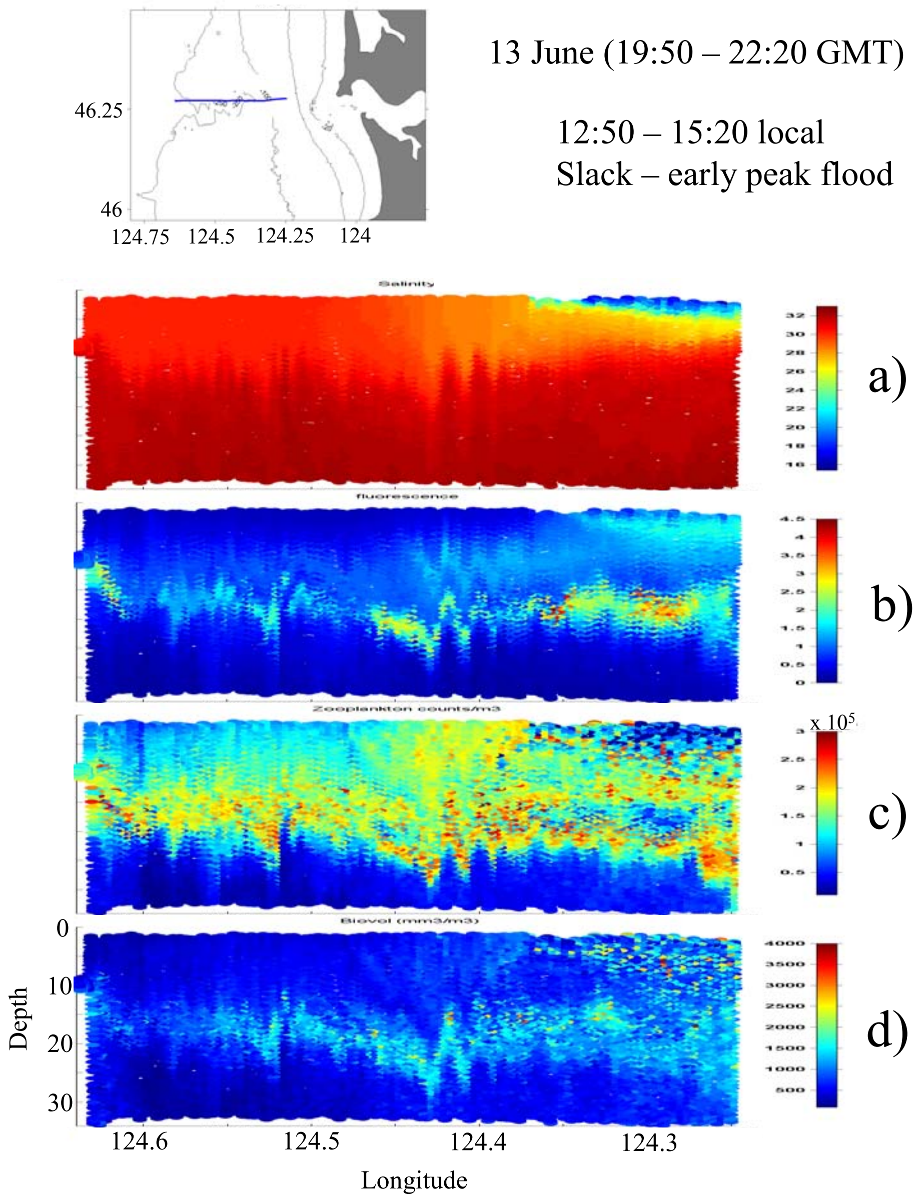


Figure 15: LOPC results: the distribution of a) salinity, b) chlorophyll a fluorescence (arbitrary units), c) zooplankton abundance (No. m^{-3}), and d) zooplankton biovolume (mm^3 m^{-3}) along an East-West transect off the mouth of the Columbia River. Internal waves are evident at 10 m depth at longitude 124.3° to 124.3° W. These waves are associated with the plume-front and displace the aggregations of phytoplankton and zooplankton that occur in distinct bands between 10 and 30 m depth. They may also, through mixing, alter the water properties of the water mass inhabited by the plankton.

References

Kay, D.J., and D.A. Jay (2003), Interfacial mixing in a highly stratified estuary 1: Characteristics of mixing, *J. Geophys. Res.*, 108(C3), 3072, doi:10.1029/2000JC000252.

Klymak, J.M., and M.C. Gregg (2004), Tidally generated turbulence over the Knight Inlet sill, *J. Phys. Oceanogr.,* 34, 1135-1151.

Macdonald, D.G. and Geyer, W.R., 2004. Turbulent Energy Production and Entrainment at a Highly Stratified Estuarine Front. *Journal of Geophysical Research* 109, C05004, doi:10.1029/2003JC002094.

Nash, J. D. and J. N. Moum, 2005, River plumes as a source of large amplitude internal waves in the ocean, in press, *Nature*.

Orton, P. M. and D. A. Jay, 2005, Observations at the tidal plume front of a high-volume river outflow, in press, *Geophys. Res. Let*.

Ott, M.W., J.A. Barth, and A.Y. Erofeev (2004), Microstructure measurements from a towed undulating platform, *J. Atmos. Oceanic Technol.*, 21, 1621-1632.

Thorpe, S.A. 1977. Turbulence and mixing in a Scottish loch. Philos. Trans. R. Soc. London A, 286:125-181.

Appendix A: Rise 2 Transects

Transect Name	Start Date	Start Time	End Date	End Time	Start Long	Start Lat	End Long	End Lat	Course over ground	SBE9 Profiles
0530_01	5/30/05	4:04:10	5/30/05	10:57:59	-124.668	44.978	-125.473	45.483	311.6	496
0530_02	5/30/05	10:59:43	5/31/05	3:19:24	-125.476	45.485	-125.542	46.934	359.4	552
0531_01	5/31/05	12:56:00	5/31/05	18:52:33	-125.461	46.997	-124.509	47.001	91.1	371
0531_02	5/31/05	19:04:41	5/31/05	23:08:18	-124.506	46.985	-124.849	46.601	211.5	392
0531_03	5/31/05	23:50:36	6/1/05	2:37:35	-124.779	46.569	-124.342	46.484	105.7	261
0601_01	6/1/05	2:45:41	6/1/05	4:11:16	-124.328	46.472	-124.241	46.320	158.3	137
0601_02	6/1/05	4:23:08	6/1/05	9:00:20	-124.258	46.312	-124.871	46.456	288.5	376
0601_03	6/1/05	9:06:58	6/1/05	16:17:48	-124.874	46.449	-124.081	46.031	127.2	577
0601_04	6/1/05	16:44:58	6/1/05	22:07:14	-124.091	46.014	-124.846	46.188	288.5	457
0601_05	6/1/05	22:17:16	6/2/05	5:52:04	-124.851	46.178	-124.062	45.522	139.9	604
0602_01	6/2/05	6:25:41	6/2/05	11:47:59	-124.111	45.480	-124.967	45.499	271.9	479
0602_02	6/2/05	11:55:56	6/2/05	16:09:10	-124.983	45.507	-125.363	45.878	324.0	339
0602_03	6/2/05	16:30:00	6/3/05	4:24:46	-125.337	45.894	-124.035	45.611	106.6	600
0603_01	6/3/05	4:37:26	6/3/05	12:26:27	-124.028	45.621	-124.935	46.117	308.0	766
0603_02	6/3/05	12:49:46	6/3/05	19:04:04	-124.942	46.123	-124.048	45.784	118.5	613
0603_03	6/3/05	19:12:34	6/4/05	2:55:23	-124.046	45.791	-124.774	46.242	311.4	540
0604_01	6/4/05	3:17:26	6/4/05	8:46:56	-124.770	46.253	-124.081	46.011	117.1	329
0604_02	6/4/05	8:55:20	6/4/05	13:07:38	-124.073	46.014	-124.533	46.278	309.7	374
0604_03	6/4/05	13:31:50	6/4/05	14:48:42	-124.541	46.285	-124.354	46.231	112.4	93
0604_04	6/4/05	16:30:06	6/4/05	18:09:23	-124.444	46.253	-124.209	46.192	110.7	163
0605_01	6/5/05	2:15:25	6/5/05	4:33:39	-124.132	46.122	-124.248	46.316	337.8	206
0605_02	6/5/05	8:46:52	6/5/05	10:15:22	-124.310	46.216	-124.521	46.279	293.1	144
0605_03	6/5/05	10:22:15	6/5/05	12:00:51	-124.517	46.281	-124.287	46.208	114.8	161
0605_04	6/5/05	12:19:54	6/5/05	13:57:00	-124.259	46.197	-124.264	46.352	358.7	157

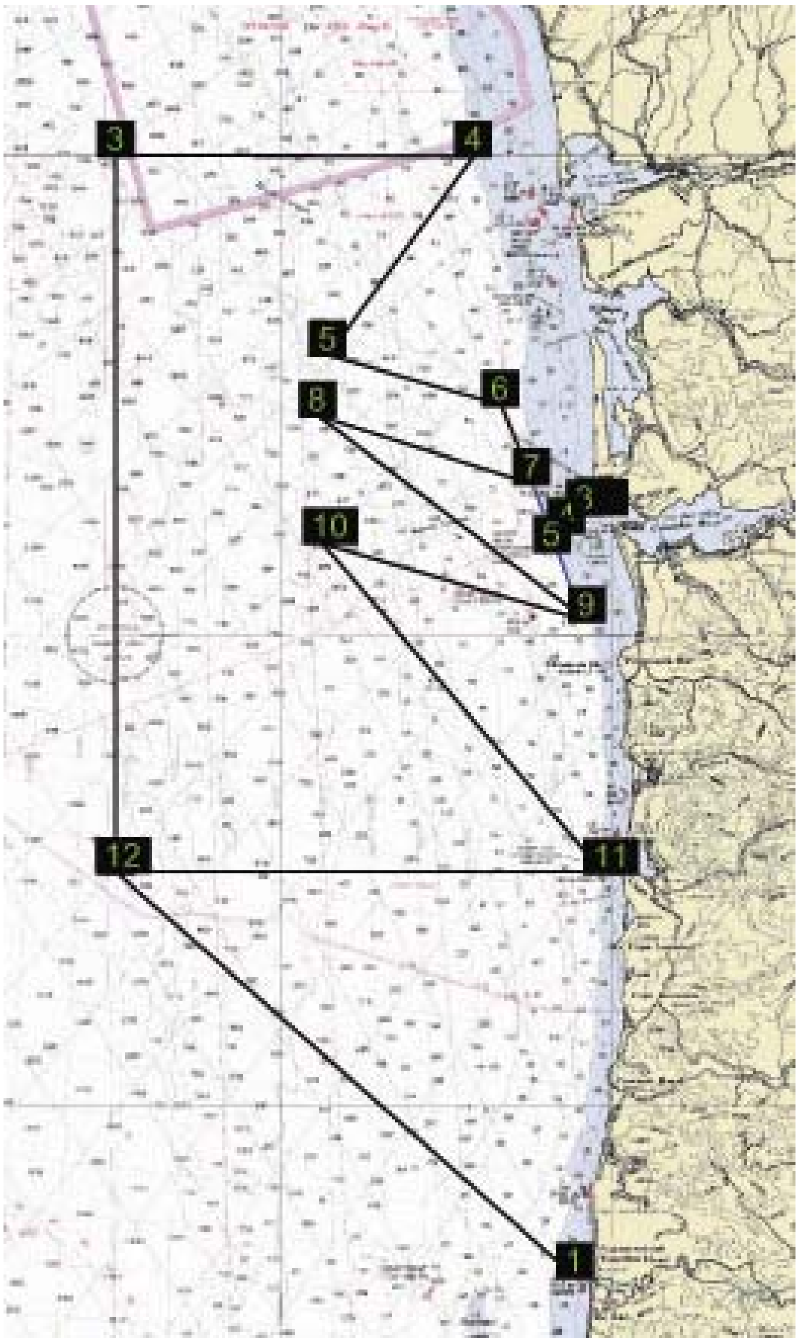
0605_05	6/5/05	14:36:55	6/5/05	19:02:14	-124.263	46.351	-124.105	46.067	157.9	277
0605_06	6/5/05	19:12:39	6/5/05	22:27:03	-124.099	46.074	-124.263	46.346	337.4	263
0605_07	6/5/05	22:37:27	6/6/05	1:49:21	-124.255	46.352	-124.103	46.068	159.8	254
0606_01	6/6/05	2:14:08	6/6/05	4:56:54	-124.104	46.072	-124.261	46.352	338.8	217
0606_02	6/6/05	5:12:10	6/6/05	6:41:02	-124.268	46.359	-124.212	46.257	159.0	119
0606_03	6/6/05	6:59:39	6/6/05	7:59:16	-124.212	46.246	-124.265	46.344	339.3	83
0606_04	6/6/05	8:08:54	6/6/05	10:19:10	-124.258	46.348	-124.168	46.190	158.3	179
0606_05	6/6/05	10:28:52	6/6/05	11:57:20	-124.163	46.192	-124.262	46.346	336.2	121
0606_06	6/6/05	12:22:57	6/6/05	14:33:19	-124.269	46.367	-124.202	46.245	159.4	174
0606_07	6/6/05	15:35:15	6/6/05	18:59:23	-124.272	46.352	-124.105	46.071	157.8	280
0606_08	6/6/05	19:07:49	6/6/05	19:59:39	-124.098	46.075	-124.157	46.173	337.1	71
0606_09	6/6/05	20:03:51	6/6/05	23:10:15	-124.167	46.177	-124.647	46.191	272.9	210
0606_10	6/6/05	23:38:45	6/7/05	1:40:27	-124.644	46.193	-124.278	46.188	91.0	88
0607_01	6/7/05	2:01:03	6/7/05	4:23:30	-124.271	46.189	-124.665	46.191	270.4	112
0607_02	6/7/05	4:28:41	6/7/05	6:23:45	-124.677	46.196	-124.876	46.353	318.5	97
0607_03	6/7/05	6:35:29	6/7/05	15:24:03	-124.868	46.365	-124.263	46.371	98.6	180
0607_04	6/7/05	15:32:30	6/7/05	18:27:15	-124.264	46.361	-124.161	46.182	159.2	226
0608_01	6/8/05	0:47:23	6/8/05	2:28:38	-124.138	46.148	-124.231	46.296	336.6	164
0608_02	6/8/05	9:31:14	6/8/05	11:25:11	-124.232	46.296	-124.128	46.118	158.3	148
0608_03	6/8/05	21:54:38	6/9/05	2:02:56	-124.108	46.059	-124.311	46.429	339.1	338
0609_01	6/9/05	2:22:33	6/9/05	6:03:29	-124.310	46.428	-124.104	46.067	158.6	296
0609_02	6/9/05	6:21:20	6/9/05	9:14:24	-124.108	46.077	-124.259	46.342	338.4	236
0609_03	6/9/05	9:23:36	6/9/05	12:13:58	-124.266	46.341	-124.104	46.068	157.6	237
0609_04	6/9/05	12:28:21	6/9/05	15:05:55	-124.101	46.067	-124.232	46.308	339.2	219
0609_05	6/9/05	15:11:59	6/9/05	16:23:43	-124.244	46.309	-124.413	46.266	249.5	99
0609_06	6/9/05	16:32:11	6/9/05	17:21:00	-124.416	46.255	-124.361	46.183	151.4	65
0609_07	6/9/05	17:32:24	6/9/05	19:45:35	-124.350	46.189	-124.350	46.438	0.1	185
0609_08	6/9/05	19:58:09	6/9/05	23:03:49	-124.331	46.438	-124.333	46.129	180.3	217

0609_09	6/9/05	23:04:48	6/10/05	1:55:10	-124.333	46.131	-124.334	46.415	359.8	170
0610_01	6/10/05	4:08:47	6/10/05	6:03:30	-124.331	46.409	-124.334	46.198	180.4	116
0613_01	6/13/05	13:47:45	6/13/05	16:24:33	-124.216	46.272	-124.646	46.272	270.1	221
0613_02	6/13/05	16:37:36	6/13/05	19:41:03	-124.646	46.272	-124.237	46.272	90.0	257
0613_03	6/13/05	19:47:44	6/13/05	22:17:47	-124.241	46.277	-124.631	46.271	268.8	212
0613_04	6/13/05	22:28:33	6/14/05	0:51:58	-124.624	46.274	-124.249	46.271	90.5	202
0614_01	6/14/05	1:10:01	6/14/05	4:03:45	-124.236	46.272	-124.645	46.272	269.9	245
0614_02	6/14/05	4:12:46	6/14/05	7:06:17	-124.643	46.270	-124.218	46.269	90.1	246
0614_03	6/14/05	7:12:25	6/14/05	9:47:18	-124.220	46.274	-124.624	46.275	270.2	217
0614_04	6/14/05	9:53:12	6/14/05	12:35:39	-124.626	46.271	-124.230	46.271	90.0	221
0614_05	6/14/05	12:53:45	6/14/05	14:31:31	-124.226	46.271	-124.462	46.272	270.2	137
0614_06	6/14/05	14:45:58	6/14/05	16:17:42	-124.475	46.271	-124.224	46.272	89.9	129
0614_07	6/14/05	16:26:44	6/14/05	18:03:04	-124.209	46.259	-124.115	46.090	158.8	136
0614_08	6/14/05	18:13:21	6/14/05	19:09:52	-124.112	46.086	-124.154	46.169	340.4	79
0614_09	6/14/05	19:40:02	6/14/05	22:51:06	-124.150	46.141	-124.312	46.434	339.0	268
0614_10	6/14/05	23:05:36	6/15/05	2:42:38	-124.313	46.436	-124.104	46.067	158.6	293
0615_01	6/15/05	2:53:43	6/15/05	3:57:41	-124.102	46.067	-124.152	46.167	340.7	89
0615_02	6/15/05	6:15:52	6/15/05	8:34:31	-124.154	46.115	-124.249	46.326	342.6	201
0615_03	6/15/05	8:59:42	6/15/05	11:49:34	-124.262	46.334	-124.106	46.071	157.7	242
0615_04	6/15/05	12:06:27	6/15/05	14:15:19	-124.106	46.066	-124.216	46.274	339.8	177
0615_05	6/15/05	22:17:37	6/16/05	0:13:38	-124.246	46.266	-124.116	46.091	153.0	161
0618_01	6/18/05	13:44:08	6/18/05	16:55:36	-124.216	46.185	-124.717	46.098	255.6	196
0618_02	6/18/05	17:07:31	6/18/05	21:27:47	-124.722	46.104	-124.274	46.469	40.4	196
0618_03	6/18/05	21:36:45	6/18/05	23:32:09	-124.275	46.477	-124.563	46.413	252.7	86
0618_04	6/18/05	23:33:32	6/19/05	3:19:35	-124.566	46.415	-124.326	46.782	24.3	166
0619_01	6/19/05	13:42:23	6/19/05	17:30:22	-124.269	46.262	-124.694	45.965	223.7	222
0619_02	6/19/05	17:40:22	6/19/05	22:22:32	-124.687	45.953	-124.050	45.825	104.4	205
0619_03	6/19/05	22:31:41	6/20/05	11:41:08	-124.040	45.817	-125.146	44.666	214.6	437

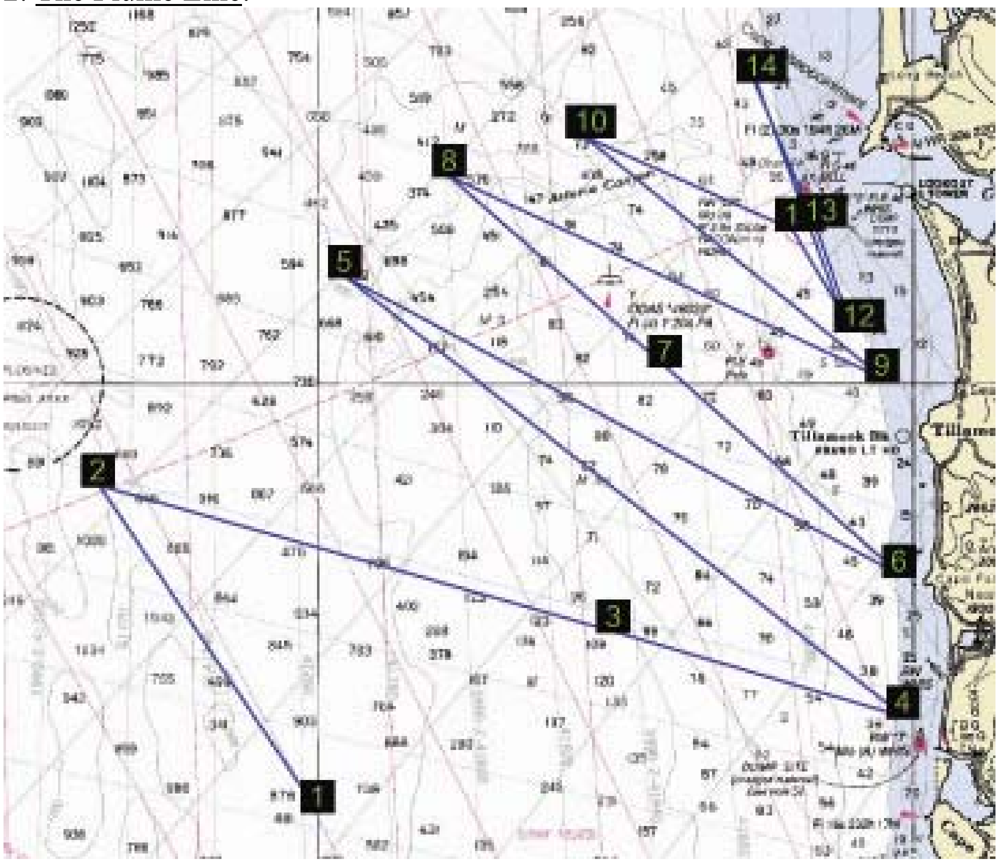
Appendix B: Sampling Plans

These maps were compiled for planning purposes. Deviations from planned courses occurred frequently, due to such factors as traffic, sea conditions, and crab-pot concentrations. Some planned lines were honored in the breach rather than the observation. Also, lines like the NS-Line were repeated multiple times. The scale is not constant in the following maps, which are for illustrative purposes only.

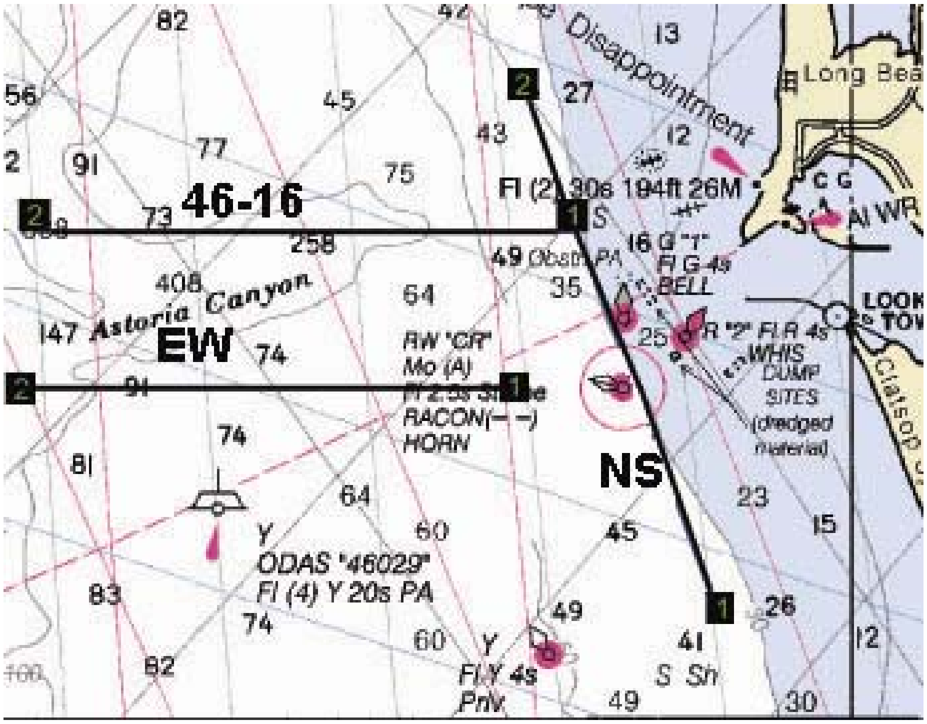
1. Initial Plume Map:



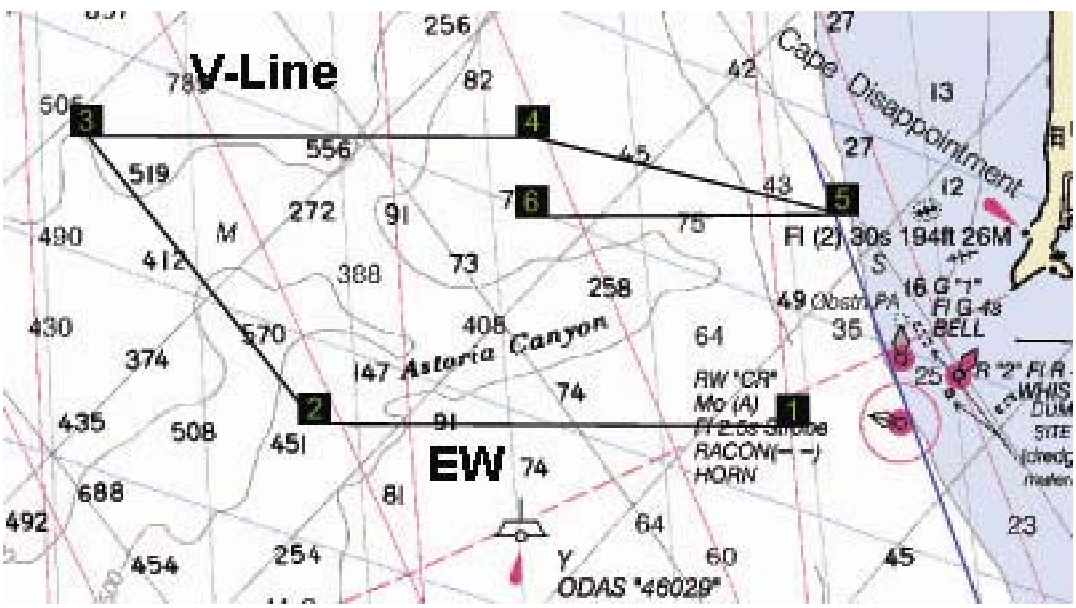
2. <u>The Plume Line</u>:



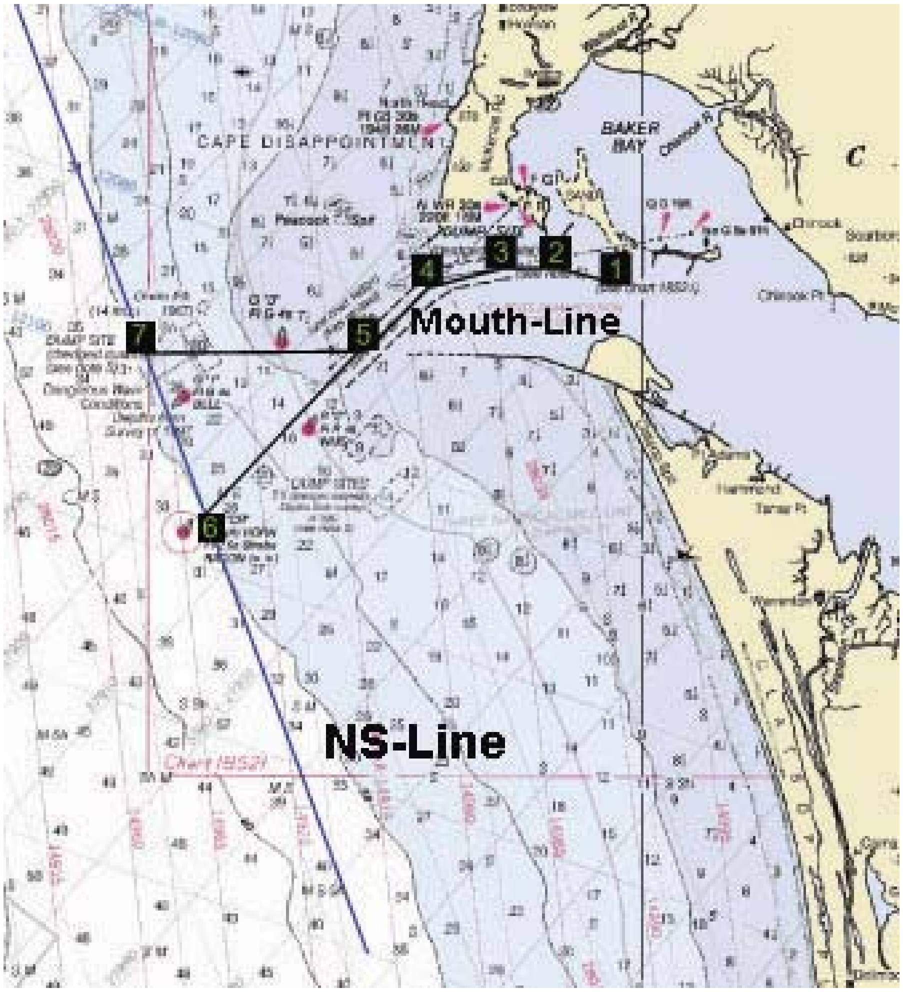
3. Inner Plume Sampling Lines:



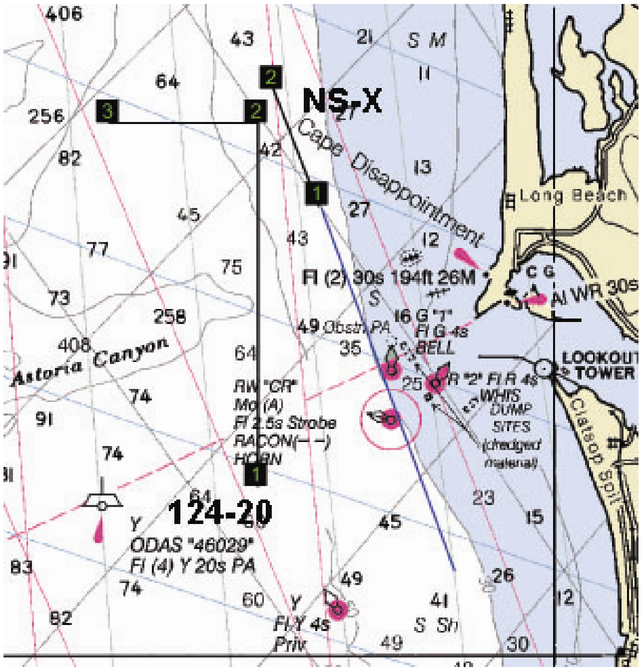
4. EW-Line and V-Line:



5. Plume Lift-Off Sampling:



6. 124-20 Line:



7. Estuary Sampling Stations: