A comparison of discharge plumes from Elkhorn Slough and the Moss Landing Power Plant

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Abstract

There is concern that thermal discharge from coastal power stations impact coastal ocean ecosystems. The introduction of heated water from these sources, for example, can influence the aquatic environment by decreasing oxygen solubility and affecting metabolic activity of marine organisms. Here we describe and compare the general flow structure, dynamics and temperature differences between a thermal discharge from an anthropogenic point source (the Moss Landing Power Plant) and the natural heat flux between two natural bodies of water, an estuary (the Elkhorn Slough) and the open ocean. The data used in this analysis were collected on different occasions for two indivdual and separate studies. Data colletion of temperature, as well as other physical, chemical and biological parameters in both studies involved a variety of *in situ* and remote sensing techniques, from stationary temperature loggers on buoys, underway mapping systems, an autonomous underwater vehicle, and remotely sensed data collected by visible and infrared airborne sensors. The results show that tidal inertia produces a surface advected plume exiting the Elkhorn Slough through the Moss Landing Harbor channel that extends approximately one kilometer in a southwesterly direction. The plume is approximately 500 m wide and extends 5-10 m in depth. By contrast, the Moss Landing Power Plant outfall discharge extends vertically through the water column directly over the discharge site, and at the surface a plume disperses shoreward and south of the discharge site. Temperature measurements from each of the plumes show high levels of variability due to tidal mixing. The difference in average daily temperature between the Elkhorn Slough plume and nearshore waters was usually ~1°C , but overall temperatures differences ranged from 1.3°C cooler to 2.3°C warmer. Temperature variability measured at the Moss Landing Power plant outfall discharge site, ranged from 3.7°C cooler to 6.4°C warmer than ambient ocean conditions and the overall average temperature during the sampling period was ~0.5°C warmer than the surrounding nearshore waters. Temperatures cooler than surrounding bay waters at the outfall discharge site occurred only 15% of the time during the sampling period, compared to 20% of the time for the Elkhorn Slough plume. Overall, prelimiary results show that the thermal contribution to the coastal ocean from the Elkhorn Slough maybe greater than that from the outfall discharge. Future research directions are recommended to further understand the interaction of these plumes with each other, as well as their contribution to the coastal waters of Monterey Bay and the Monterey Bay National Marine Sanctuary.

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1. Introduction

The Elkhorn Slough (ES) is located at the center of Monterey Bay (Figure 1). It is the largest estuary between San Francisco and San Luis Obispo and harbors the largest tract of tidal salt marsh in California outside of San Francisco Bay. The fact that wetland habitats are exceedingly rare in California makes ES an area of utmost ecological significance for birds, marine mammals and fishes that rely upon estuaries. In 1946, the Army Corp of Engineers changed the morphology of ES by cutting through the dune barrier separating it from Monterey Bay. Since then, ES has been transformed from a sluggish backwater to a shallow, tidally forced embayment. The slough exchanges waters with Monterey Bay twice daily, year-round, and since 1946 the ES tidal prism has almost tripled and the volume of the tidal exchange is now four times greater than the combined discharge of all rivers entering Monterey Bay (Larry Breaker, pers. comm.). The hydrological changes in ES have important implications for temperatures, not only in the slough, but also in the nearshore coastal waters of Monterey Bay. In addition to introducing changes in temperature, the plume that exits ES is also a source of sediment, phytoplankton and, in winter months elevated concentrations of nutrients. Tidal scouring of the slough's banks and bed resuspends pollutants that have accumulated in sediments over the past several decades. In addition to the seawater exchange through the mouth, ES receives terrestrial freshwater runoff from the Salinas River through the old Salinas River channel, seasonal streams in the upper main channel (Carneros and Corncob Canyon Creek), and agricultural runoff flow from summer irrigation. ES serves as a significant link between land use activities and the coastal waters of Monterey Bay and this link has received little attention. Yet, changes in land-use in the surrounding 585-km^2 ES watershed, coupled with climate change will continue to modify the hydrology of this system and its influence on the coastal ocean.

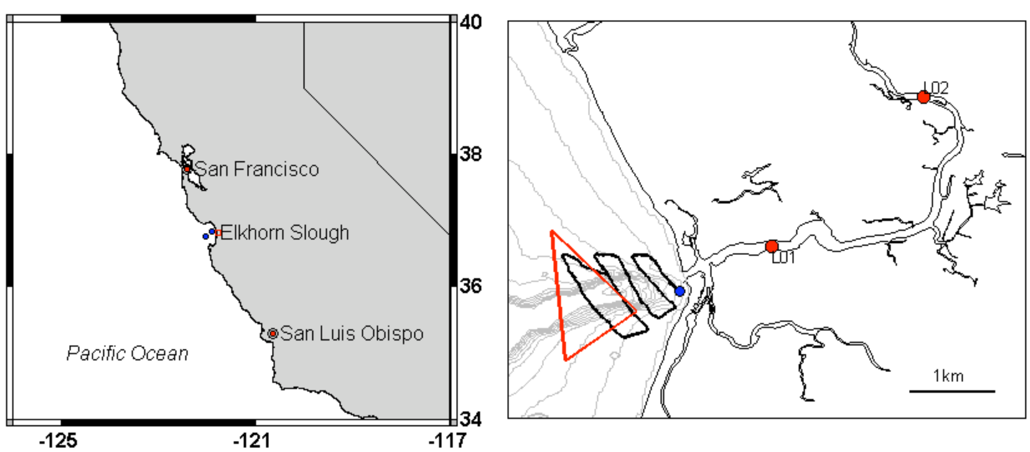

Figure 1: Left; Monterey Bay and the location of the Elkhorn Slough, along with the locations of time series stations M0 (shoreward blue dot) and M1 (seaward blue dot). Right; Elkhorn slough and the LOBO time series stations (red dots), along with sampling tracks for the underway mapping systems (black line) and the autonomous underwater vehicle (red line). The blue dot indicates the approximate location of the MLPP discharge.

On the banks of the Elkhorn Slough sits the Moss Landing Power Plant (MLPP). The MLPP is California's largest non-nuclear power plant. The total generating capacity of the MLPP is 2538 MW. As of April of 2003, Duke Energy of Moss Landing, LLC had recently completed re-powering and modernizing the MLPP. The MLPP takes ES water in through the intake structures located in Moss Landing Harbor. These waters are used for cooling during plant operations. The thermal waste is discharged into Monterey Bay through the diffuser pipes located just south of theMoss Landing Harbor entrance. Under peak power production, discharge is estimated at approixmately 850,000 gallons per minute (gpm). The maximum heat loading of the facility is 182 million BTU/min. More details with regard to the historic and post-modernization flow rates, heat loads, cooling water temperature increases, and generation capacities can be found in the Duke Energy report, "Moss Landing Power Plant Modernization Project: Evlauation of the Proposed Discharge System with Respect to the Thermal Plan" (Duke Energy, 2000).

Since the early 1970's, the thermal discharge of coastal power stations has garnered attention with regard to its impacts on the composition of the biotic communities and on the activities of micro-organisms in the aquatic ecosystem (Horvath and Brent, 1970). More recently, studies have looked at the impacts of thermal pollution on meiobenthic and macrobenthic community abundances (Lardicci et al., 1999), and standing stock biomass (Keser, 2003). As a result of these concerns and the requirements of the Clean Water Act Section 316b for thermal discharges, the MLPP operates under waste discharge requirements (WDRs) issued by the Central Coast Regional Water Quality Control Board (CCRWQCB) and is subject to the California Thermal Plan (Water Quality Control Plan for Control of Temperature in the Coastal and Interstate Waters and Enclosed Bays and Estuaries of California) with respect to the thermal component of the discharge. The Thermal Plan states that thermal discharges should conform to the following limitations:

(i) "The maximum temperature shall not exceed the natural receiving water temperature by more than 20°F [11°C]."

(ii) "The discharge of elevated temperature wastes shall not result in increases in the natural water temperature exceeding 4°F [2.2°C] at (a) the shoreline, (b) the surface of any ocean substrate, or (c) the ocean surface beyond 605 meters from the discharge system. The surface temperature limitations shall be maintianed at least 50 percent of the duration of any complete tidal cycle.

On October 27, 2000 following a public hearing, CCRWQCB adopted WDR Order No. 00-041 for the modernized MLPP that contains alternative effluent limitations. The new WDRs contain three different sets of thermal effluent limitations based on the discharge activity of the different operating units:

(i) "when only Units 6 and/or 7 are operating, the maximum temperature of the effluent should not exceed the natural temperature of receiving waters by more than 28^{o} F [15.6°C] as a daily average and 34^{o} F [19.3°C] as an instantaneous maximum (hourly average);

(ii) when only Units 1 and/or 2 are operating, the maximum temperature of effluent should not exceed the natural temperature of receiving waters by more than 20^{o}

F [11°C](Thermal Plan) as a daily average and 26° F [15°C] as an instantaneous maximum; and

(iii) when Units 1 and/or 2 are operating along with Units 6 and/or 7, the maximum temperature of the combined effluent should not exceed the natural temperature of receiving waters by more than 26° F [11°C] as a daily average and 32° F [17.8°C] as an instantaneous maximum. Additionally, during heat treatment, which will be conducted once every one to four months, the hourly average temperature of the discharge shall not exceed the temperature of the receiving water by more than 40°F [22.2°C]."

Several studies have examined the physical extent of the MLPP thermal plume (Paduan, 2003 and Duke Energy, 2000), as well as the ecological effects of the discharge (MLML, 2006). The MLML study was commissioned to identify if changes in the distribution or community structure of the phytoplankton, benthos, and birds had occurred since the mid-1970s, and if so, were changes correlated with the thermal plume from the MLPP outfall. The report showed that bacterial growth was enhanced as a result of passage through the MLPP cooling system. Phytoplankton species were negatively impacted after passage, showing reductions in photochemical quantum efficiency (F_v / F_m), increases in pheopigment/chl a ratios, and decreases in phytoplankton gross primary productivity at the power plant exit. The study showed no detectable significant impacts on intertidal and shallow subtidal faunal communities, as well as no negative impacts on seabird abundance. Organisms (otters and seabirds) were observed utilizing the thermal plume outfall site for either feeding or thermoregulation. The lack of negative effects on the marine community reflect the results collected by Lardicci et al. (1999) and Keser (2003).

The broader goal of this study is to compare the spatial extent of both the ES discharge plume and MLPP outfall discharge, the temperature difference between both of these plumes and ambient ocean temperatures and the temperature differences between each other. To achieve that goal we compiled and compared exisitng datasets to draw some conclusions about the general flow structure and dynamics of each of these plumes. We compared plume temperatures to ambient ocean temperatures and compared thermal loading between plume and outfall. Finally, we outline future research needs to better understand both plumes and their interactions. This synthesis begins to provide a comparison of the influence of an anthropogenically derived, point source thermal discharge to that of the natural heat flux between two natural bodies of water, an estuary and the open ocean.

2. Methods

2.1 Elkhorn Slough

The discharge plume of the Elkhorn slough was sampled by the Monterey Bay Aquarium Research Institute (MBARI) on March 17 and December 9 and 10, 2004 and on January 6, 10, 20 and 21, 2005 during the ebb stage of the tidal cycle. The surface expression of the plume was measured by a near surface underway (UW) mapping system deployed from a Boston Whaler. The surface UW mapping system is a neatly packaged set of instruments measuring water clarity (through transmission), temperature and salinity, chlorophyll fluorescence, color dissolved organic matter fluorescence, and nitrate concentration. The individual instruments used to measure these parameters were a WetLabs Cstar, SeaBird 45, WetLabs WetStar, WetLabs CDOM fluorometer and an In Situ Ultraviolet Spectrophotometer (ISUS)(Johnson and Coletti, 2002), respectively. Water samples were pumped through the instruments from one foot below the surface. The speed of the boat was regulated so as to avoid bubbling in the instruments. The ES plume was sampled between four to six times on each day during the outgoing tide. The boat followed a serpentine path to capture the full extent of the plume and each sampling pass averaged 75.64 minutes (see Figure 1). MBARI's autonomous underwater vehicle (AUV) was deployed from the RV Zephyr in conjuction with the underway mapping. The AUV followed a traingluar path up and down through the water column to capture vertical profiles of plume and offshore waters (see Figure 1) . This pattern was repeated four to seven times each sampling day though the ebb stage of the tide. Instruments in the AUV measured physical, chemical and biological constituents of the water column including temperature, salinity, fluorescence, particle backscatter and nitrate concentrations. The average duration of each triangular sampling track was 58.4 minutes.

Drifters were deployed to determine plume surface flow patterns. The drifters, consisting of a PVC pipe with foam flotation, were attached to a drogue to ensure that the movement of the drifter coincided with the flow of the water and not that of the wind. The PVC pipe housed a Garmin GPS receiver which, in addition to logging its geographic position every 30 seconds, recorded local time, distance between logged points, speed and magnetic direction. Water samples were analyzed for chlorophyll and pigments. On March 17, 2004, the vertical structure of the plume was also measured with CTD (conductivity, temperature, and depth) profiles. Hyperspectral remotely sensed imagery was acquired on October 13, 2000 and October 7, 2002 by the National Aeronautics and Space Administration's (NASA) Airbrone Visible/Infrared Imaging Spectrometer (AVIRIS). Hourly temperature data for time series stations M1 (oceanic) and M0 (nearshore) were downloaded from the MBARI LiveAccess server (http://dods.mbari.org/lasOASIS/main.pl?). M1 and M0 were used as reference stations to compare to ES water temperatures. Similarly, hourly temperature data from time series stations L01 and L02 were downloaded from the Land/Ocean Biogeochemical Observatory (LOBO) Network Data Visualization (http://www.mbari.org/lobo/loboviz.htm) website. Surface temperature data from L01 and L02 were used to help understand the temperature distribution within ES and to verify the validity of surface underway measurements in the area of the Elkhorn Slough plume.

2.2 Outfall Dicharge

Previous datasets were collected to examine both the spatial extent and physical characteristics of both the MLPP outfall plume and the Elkhorn Slough plume. A study to evaluate the MLPP outfall plume was conducted by Tenera Environmental in 2002 and compiled by Jeffery Paduan in 2003 (see Paduan et al., 2003). This study involved three seperate measurement approaches: 1) the installation of continually recording temperature sensors at a number of locations around the discharge and intake structures of the power plant, and along the beach for a period of several months (Figure 2), 2) a series of spatial surveys conducted from an instrumented boat during several phases of the tide, and 3) aerial infrared (IR) overflights conducted in conjunction with boat surveys. Refer to Paduan (2003) for further details on the sampling methods.

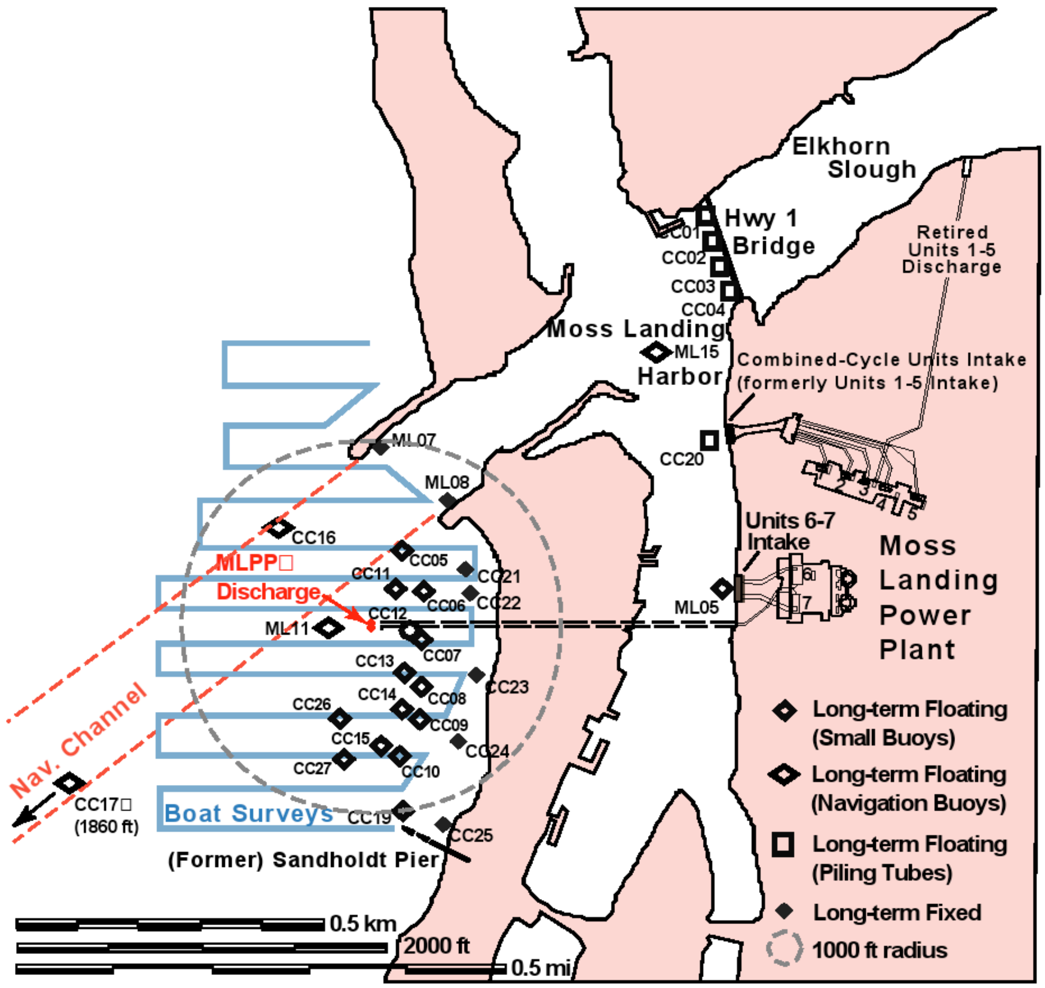

Figure 2: Components of the Moss Landing Power Plant together with locations of temperature recorder stations used in the thermal evaluation study.

The datasets examined here were collected independently for seperate studies. The MLPP outfall discharge data were collected between June and October 2002, while ES plume data were collected in winter months of December and Janaury 2004 and 2005. These time preiods represent distinct climatic and oceanographic periods in Monterey Bay (Breaker and Broenkow, 1994). Therefore, the general flow, structure, dynamics and temperature dispersion of both the ES plume and the MLPP outfall may be under the influence of different seaonsal climatic and oceanographic conditions during their independent sampling periods. In attempt to normalize the two disparate datasets, in the last section we calculate a thermal comparison of the two plumes, to get a sense of the thermal contribution of each of these plumes to the coastal ocean.

3. Results

3.1 Structure and Flow

3.1.1 Elkhorn Slough

The Elkhorn Slough plume can be seen exiting the Moss Landing harbor entrance on every ebb tide. This plume carries with it sediments that have been eroded from the bottom and the banks of the slough, and in the winter months after heavy rains, it also transports terrestrial sediments, which enter the slough through streams and runoff. The surface expression and spatial distribution of the ES plume can be clearly seen in remotely sensed imagery collected by AVIRIS. Spectrally derived products of chlorophyll, sediment and color dissolved organic matter (CDOM) show a strong surface expression of the plume extending approximately one kilometer offshore in a southwesterly direction and extending to a maximum width of approximately 500 m (Figure 3).

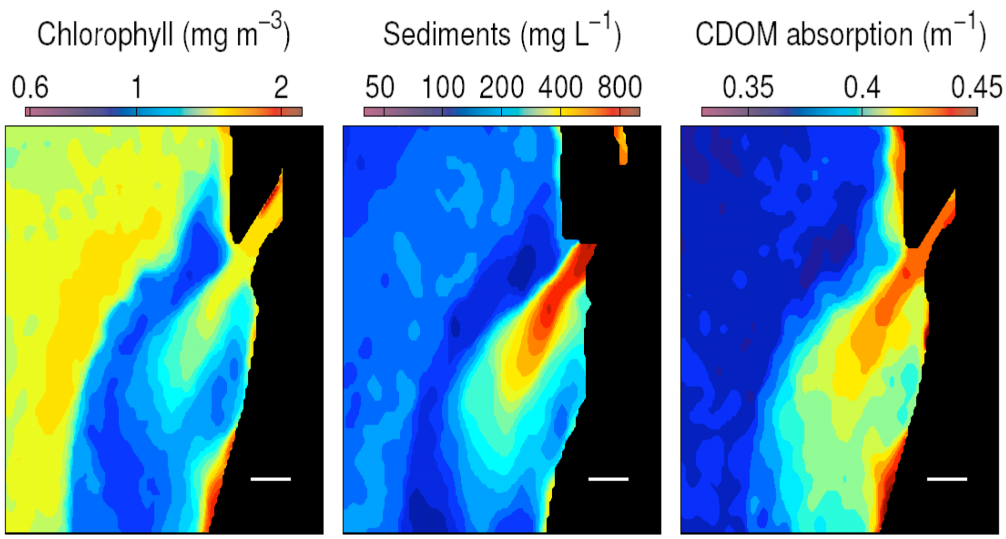

Figure 3: Spectrally derived products from the AVIRIS sensor. The scale bar equals 250 meters.

CTD profiles (Figure 4) reveal a wedge of warm, less saline water, approximately 5-10 m thick exiting the slough at maximum ebb tide. Drifters deployed in the harbor mouth showed that, during ebb tide, this wedge of water followed a trajectory southwest along the coast, eventually becoming entrained in the northward bay circulation. Currents in the harbor channel and just outide the mouth of the channel were measured between 50 and 160 cm/sec. Once entrained in the northward bay circulation system, the drifter current speed slowed to 10-25 cm/sec (Figure 5). Current measurements in the northward bay circulation system agree with those reported by Breaker and Broenkow (1994).

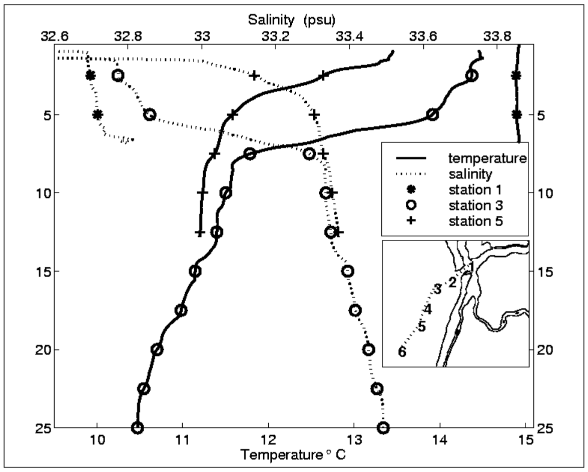

Figure 4: CTD profiles of the Elkhorn Slough plume with position of sampling stations (inset)

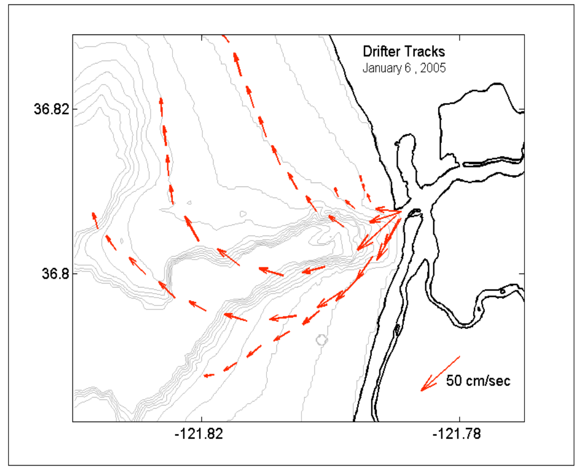

Figure 5: Drifter trajectories for January 6, 2005.

With these initial ES plume variables (plume length, width, depth and current velocity), additional calculations can be made to further describe the general flow structure and dynamics of the plume. These calculations are useful as a means of intercomparison between observations from different discharges, which in the coastal ocean, can occur in a variety of forms and scales. Additionally, the delivery of physically different types of water masses to the coastal ocean may be strongly influenced by the trajectory and forcing of the plume. The Kelvin number can be used to compare inertia and rotational forcing at an estuarine mouth and has been used by Garvine (1995) to develop a classification system of buoyant discharges. The "mouth" Kelvin number K_m is used to compare the relevance of inertial effects and rotational forcing at an estuarine mouth and is defined as the ratio of the width of the plume at the mouth (L_m) to the deformation radius (L_D), which is defined as

$$L_D = (g' h_p)^{0.5} / f$$

where g' is the maximum measured buoyancy anomaly (Pond and Prickard, 1983) of the plume, h_p is the thickness of the plume (~6 m), and f is the Coriolis parameter (~8.2 x 10^{-5} /s). Therefore, for Elkhorn Slough $K_m << 1$ which indicates that inertial effects at the mouth are much more important relative to rotational effects of the earth, which may influence larger riverine plumes.

Secondly, the "plume" Kelvin number is defined as the ratio of plume width (L_p) to L_D. The (L_p) of the Elkhorn Slough plume was estimated to be on the order of one kilometer from the remotely sensed imagery. This suggests that $K_p << 1$ and that once out of the mouth of the harbor, the ES plume is still significantly influenced by inertia. In summary, the ES plume can be characterized as a relatively small-scale, jet-like structure that is primarily advection dominated and produces strong boundary fronts (Garvine, 1995).

As observed in the CTD profiles and remotely sensed imagery, the bouyant outflow of the Elkhorn slough remains primarily on top of the nearshore water forming a "thin" layer above the ambient but denser water. Yankovsky and Chapman (1997) describe a method of calculating the plume "lift-off" depth for surface advected plumes. The plume lift-off depth is defined as

$$h_b = \left(2Q_p f / g'\right)^{0.5}$$

where Q_p is the total transport of brackish water in the ES plume, defined here as the tidal prism divided by the mean current velocity sampled by the drifters in the plume. The average lift-off depth for the six sampling days was 12.28 m. This indicates, as was observed in the winter months, that the ES plume is detached from the bottom and is surface advected.

Lastly, knowing that inertial forces are important to plume dispersion and that it is a surface advected plume, Garvine (1995) suggests that the discharge momentum flux will influence a spatial scale approximately equal to the inertial radius (L_i), which is defined as

$$L_i = u_f / f$$

where u_f is a representative velocity within the plume, measured directly from drifter buoys, which during the six sampling periods averaged 28cm/s (1 km/hr). The ES plume inertial radius is ~8 km suggesting that the extent and influence of the plume may extend far offshore.

The mean values for each of these parameters were calculated for each of the six sampling days. The results are summarized in Table 2. Based on observations

Table 2: Plume parameters calculated from observations of the Elkhorn Slough discharge sampled in December and January of 2004 and 2005.

Parameter	Name	Elkhorn Slough values	Signifigance	Reference
K_m	"Mouth" Kelvin	<< 1	Inertia > rotation (at mouth)	Garvine, 1995
K_p	"Plume" Kelvin	<< 1	Inertia > rotation (within plume)	Garvine, 1995
h_b	Plume "lift-off" depth	~ 12.28m	surface advected plume	Yankovsky and Chapman, 1997
L_i	Inertia radius	~8 km	Inertia length scale	Geyer et al., 2000

and these calculations, the ES plume is a relatively small-scale plume feature whose flow dynamics relies on tidal inertia and possibly inertia from freshwater inflow from creeks and rivers during the winter months. Small-scale plumes, such as those characteristic of discharges from engineering structures and narrow river mouths, have nonlinear flow dynamics and include sharp frontal boundaries (Garvine, 1995).

3.1.2 MLPP Outfall

Models have been developed to describe the dispersion and distribution of temperatures in the marine environment following the discharge of thermal effluent from power plants (Ozturk, 1995). However, these models require the input of numerous variables which were not aviailable for this study, including velocity of jet flow from the diffuser ports, effluent density, and port diameter. For understanding the structure of the discharge plume we will rely on descrptive information from previous studies.

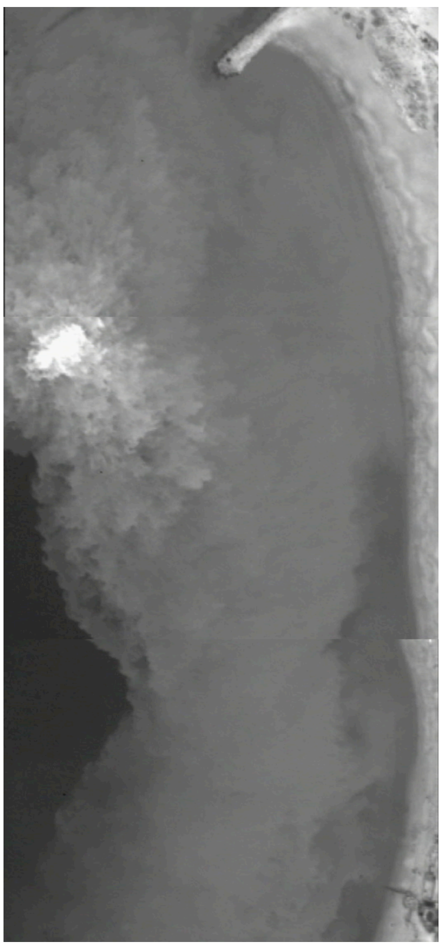

Figure 6: This infrared images shows the MLPP outfall breaking the surface just southwest of the southern harbor jetty (top of image). Lighter color represents warmer water. The warmer outfall water disperses toward the shore and to the south.

In general, cooling water for the MLPP facility is drawn from intake structures within the harbor and discharged into Monterey Bay through two subsurface conduits. The two subsurface discharge conduits are approxomately 40 feet apart from center and point upward, toward the sea surface. Though the maximum discharge from MLPP under peak power production is 850,000 gpm, the actual flow is regulated by market power demand. The MLPP discharge is from an engineering structure, and therefore, according to Garvine (1995) would fall into the category of a small-scale jet-like structure, which is similar to the discharge plume of the Elkorn Slough. However, instead of advecting across the sea surface, the MLPP plume is injected to the ocean and mixes vertically through the water column, frequently breaking the sea surface directly over the discharge location approximately 200 m from the shoreline and approximately 305 m south of the north jetty of the entrance to Moss Landing Harbor (Figure 6).

The fate of the discharge once it has reached the surface has been described most recently in a study by Paduan (2003). His summary, based on an array of temperature measurements, shows that the distribution of the MLPP thermal plume is biased toward the inshore side of the discharge upon reaching the surface. Subsurface sampling conducted from a boat show that the MLPP plume at some distance from the discharge exceeds 2.5 m in thickness on many occassions, but due to its jet-like dispersion from the mouth of the conduits, the plume rarely makes contact with the bottom. Once at the surface the plume appears to disperse shoreward and most commonly occupies the region between the discharge and the edge of the surf zone and often extends more than 61 m southward along the coast (Paduan, 2003).

3.2 Temperature

3.2.1 Elkhorn Slough Plume

The summary of surface characteristics for the ES plume collected by the underway mapping systems are shown in Table 3. In general, the ES plume surface waters exhibit increases in chlorophyll and color dissovled organic matter (CDOM) fluorescence. Transmission is low due to high sediment loading which appears to be coupled with high concentrations of nitrate. Salinity measurements ranged from 21.4 to 33.3 ppt and averaged 32.4 ppt. ES plume temperatures ranged from 12.1 to 18.3°C and averaged 13.5°C. In comparison to oceanic or bay-wide physical conditions, mean slough waters are only slightly warmer and fresher than those sampled offshore, though the nitrate values are significantly higher. Monthly time series measurements in the winter months at a station in the open waters of Monterey Bay, 5 km from the mouth of the slough, show that Monterey Bay surface waters have an average temperature of ~13°C , a range in salinity of 32.9-33.33 ppt and generally have nitrate concentrations of < 1uM (Pennington and Chavez, 2000). The similarity of average physical conditions between slough and bay waters seems reasonble, since the water sampled by the underway mapping system most likely came from the lower slough, which experiences semi-diurnal tidal action and exchange with the coastal ocean.

*Table 3: Parameter statistics of the Elkhorn Slough plume. The values represent an average over the 6 sampling dates. *Indicates mean lowest 5%.*

Parameter	Min	Max	Mean	St. Dev	Range	Mean Highest 5%
Temperature	12.1	18.3	13.5	0.6	6.2	15.9
Salinity	21.4	33.3	32.4	0.75	11.9	30.5
Fluorescence (rfu)	0.09	0.61	0.17	0.04	0.52	0.29
CDOM (rfu)	0.02	4.3	0.3	0.3	4.3	1.3
Transmission (%)	0.98	84	35.2	1.1	21.3	6.6*
Nitrate	7.3	283	25.5	18.7	275.5	79.8

The slough has at least two distinct regions that respond differently to temperature changes, the lower slough and the upper slough (Lemos et al., in prep.). The lower slough exchanges water with the ocean twice daily and thus the temperatures in this region of the slough are buffered by oceanic waters. The upper slough, where residence times have been estimated to be three weeks, may flush to the open ocean during the extreme spring tides. Therefore, it is likely that the extreme ranges in slough plume temperatures and salinity reported in Table 3 may be from tidal exchanges during spring tide events (e.g., December 10, 2004 and January 10, 2005), when the tidal influence may reach the upper slough. Temperatures in the upper slough are also more likely to respond to air temperature fluctuations due to the fact that the slough is shallower in this area and is generally less influenced by tidal mixing. Figure 6 shows times series plots of temperatures in the upper (L02) and lower (L01) portions of the slough plotted against air temperature and tidal height. Slough water temperatures measured at L01 are not closely correlated with neither air temperatures nor tidal height (R=0.2652, R=-0.1846, respectively). Temperatures measured in the upper slough at L02, however, show a higher correlation with air temperatures (R=0.44), and a lower correlation to tidal height changes (R=-0.052). Temperature at L02 lags behind air temperature by two hours.

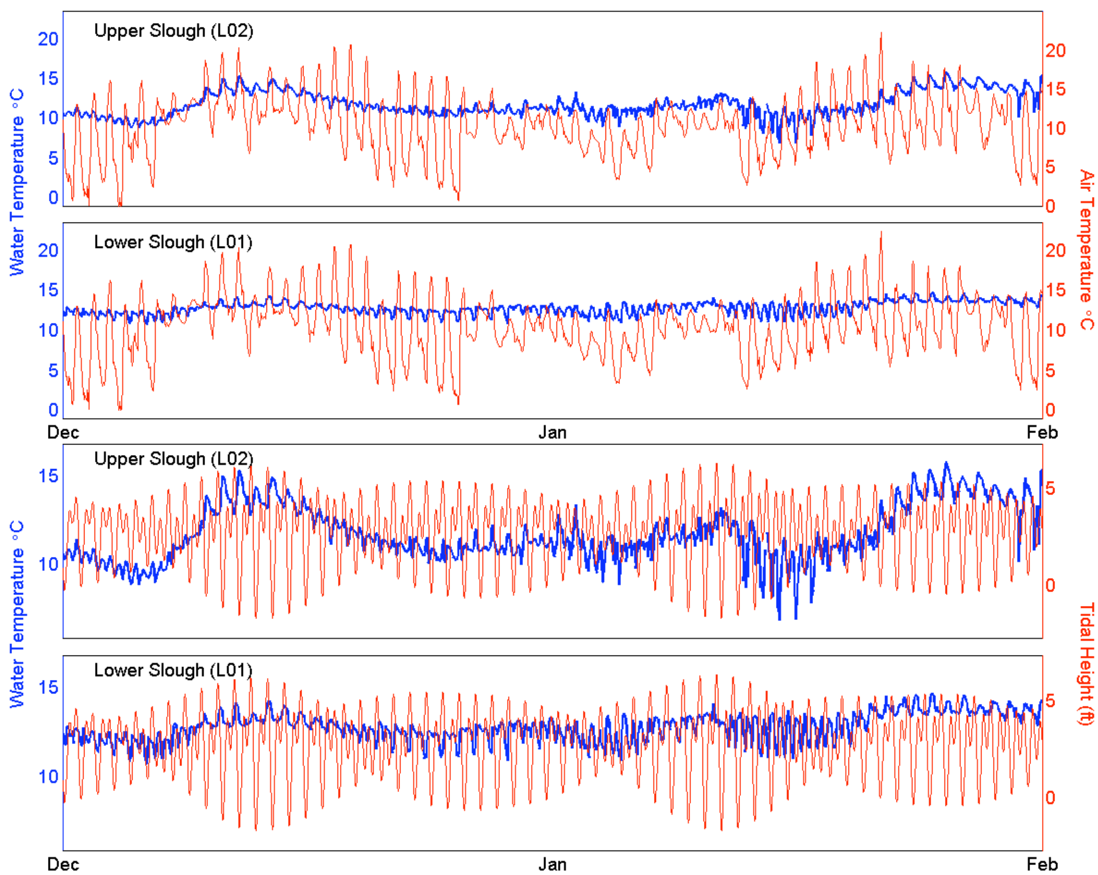

Figure 6: Water temperature in the lower slough (L01) and upper slough (L02) between December 1, 2004 and January 31, 2005, plotted against air temperature (upper panel) and tidal height (lower panel).

Further examination of slough, nearshore and oceanic waters during the winter sampling period indicate that temperatures within the slough on average are cooler than temperatures measured at the M1 (oceanic) and M0 (nearshore) time series stations. Figure 7 shows the hourly water temperatures recorded at stations L02, L01, M0 and M1 between December 1, 2004 and Janaury 31, 2005. The average temperature at each of these stations was 11.75, 12.75, 13.9 and 13.25°C, respectively. Though generally cooler, temperatures in the slough varied widely during this period and showed episodes of warming relative to oceanic (M1) and nearshore (M0) reference stations. In figure 7 this warming can be seen clearly near December 12, 2004 and Janaury 27, 2005. Periodic increases, possibly the result of tidal fluctuations and mixing can also be seen in temperatures of the lower slough (L01), particularly in the days surrounding Janaury 15, 2005.

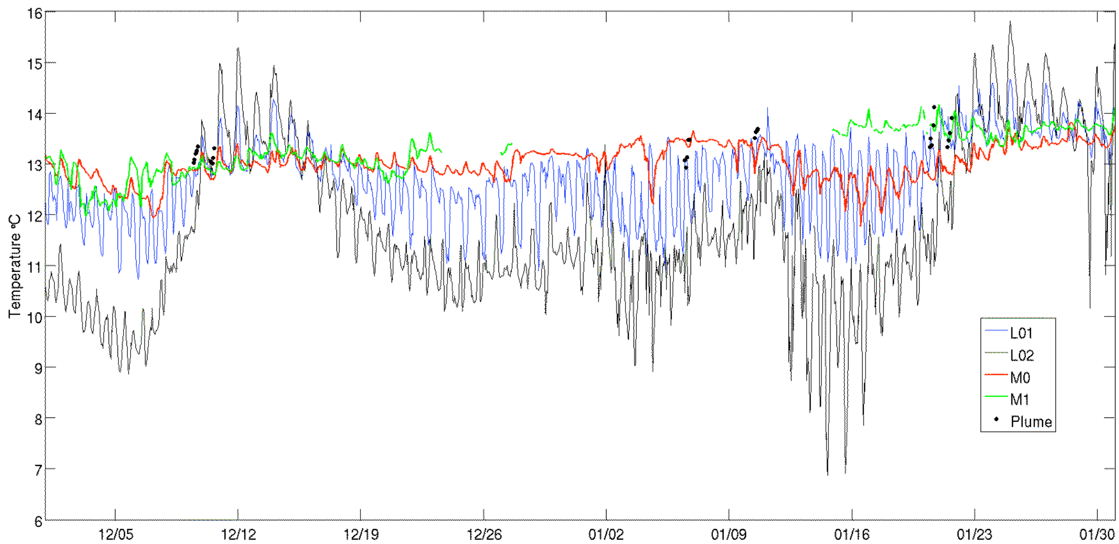

Figure 7: Hourly temperature recordings from time series stations L1, L2, M0, and M1 plotted with the average plume temperatures recorded by the underway mapping system for each sampling pass per day.

The average daily temperature as measured by the underway mapping system for each pass through the portion of the ebb cycle of the tide is also shown in Figure 7 (black dots). The results indicate that the ES plume can be either slightly warmer or cooler than surrounding nearshore waters (M0, red line). Comparisons of average daily temperatures and their differences can be found in Table 4. Though the difference in average daily

Table 4: Average temperature of plume and nearshore waters as sampled through the ebb tide, and their difference.

Date	Average Plume Temperature°C	Average nearshore Temperature (M0) °C	ΔT°C
December 9, 2004	13.18	12.87	+0.31
December 10, 2004	13.09	12.72	+0.37
January 6, 2005	13.176	13.41	-0.224
Janaury 10, 2005	13.62	13.09	+0.53
January 20, 2005	13.614	12.72	+0.92
January 21, 2005	13.57	12.83	+0.74

temperature between the slough and nearshore waters was usually <1°C, temperatures differences ranged from 1.3°C cooler to 2.3°C warmer. On all days sampled, except Janaury 6, 2005, ES plume temperatures were slightly warmer than those of the surrounding nearshore waters. This is consistent with the cooling trend observed in the slough at L01 and L02 in the latter half of December and early Janaury (Figure 7).

Figure 8 shows the vertical profile of the southern leg of the AUV sampling triangle (see Figure 1). Visible in these profiles is the pulse of slightly warmer water leaving the slough on all days except on Janaury 6, 2005 when the water leaving the slough appears to be cooler than the surrounding waters. The pulses of temperature changes seem closely correlated with the ebb tide.

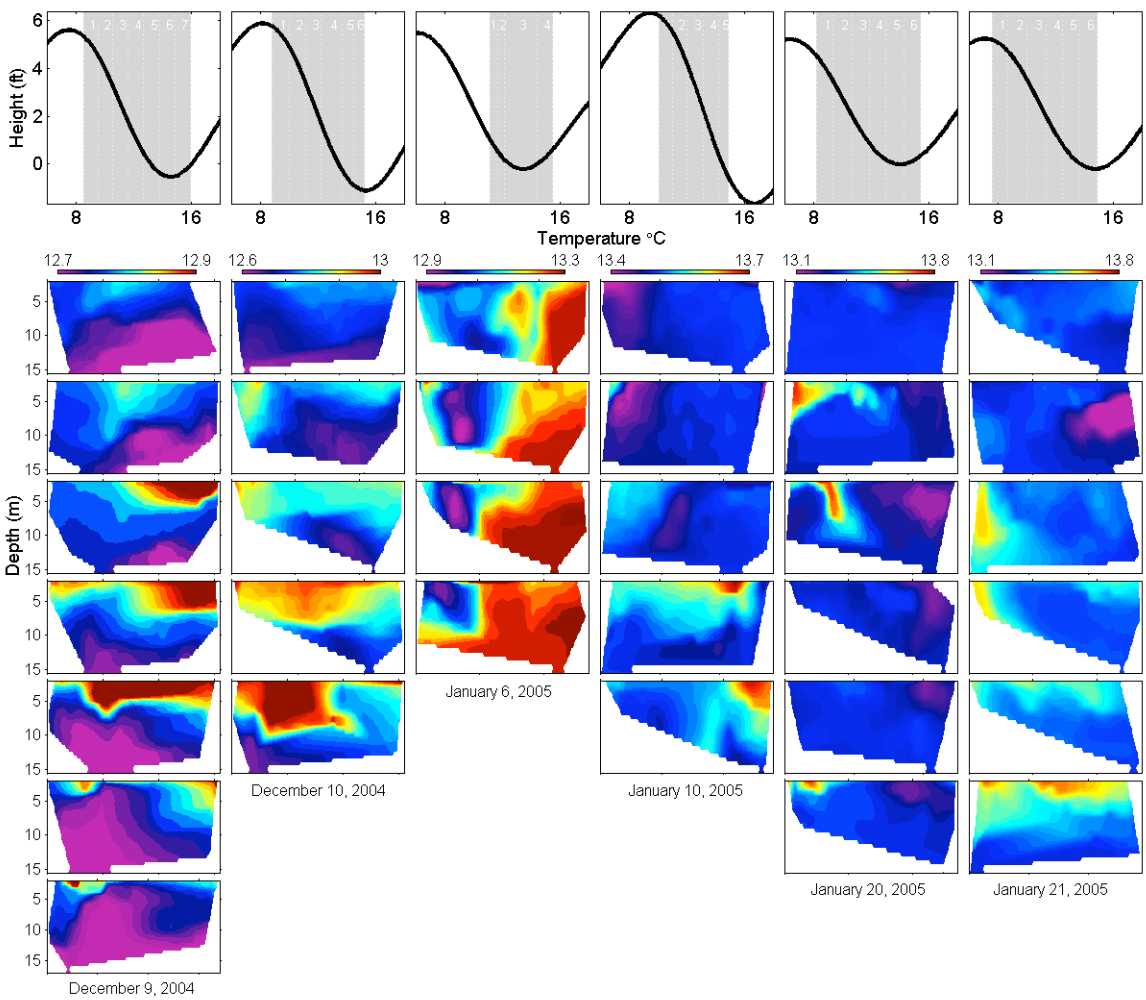

Figure 8: The southern most leg of the AUV sampling triangle shown as temperature vertical profiles through the water column (lower panel). The mouth the Elkhorn Slough is on the left side of the panel. The corresponding tidal cycle, 0800 and 1600 PDT, associated with each sampling period is shown in the upper panel.

In the data presented here, temperature differences are evident between plume and surrounding bay waters. Time series measurements suggest that temperatures in the winter fluctuate widely within the slough and the ES plume may, at any particular time, transport a pulse of warmer or cooler plume of water into the coastal ocean. Although overall temperature in the slough was cooler than surrounding bay waters during the sampling period, temperatures may on average be warmer than surrounding bay waters when considering the entire “winter” oceanographic period. Several factors may influence temperature changes within the slough, including tidal mixing, surface heat flux, air temperature, freshwater runoff and bathymetry. Several factors may also influence the temperature structure of the ES plume upon exiting the slough. The ES plume likely enters the coastal ocean and is quickly mixed with neashore ocean waters, which may be further enhanced due to canyon head processes (Carter and Gregg, 2002), and potential interactions with warmer waters from the MLPP discharge plume.

3.2.2 MLPP Outfall Plume

Previous to the Paduan (2003) study, Duke Energy deployed temperature sensors at the outfall to continuously record thermal plume variability between March and October 1999. The study was conducted to evaluate whether, at its existing capacity, the MLPP discharge system complied with the Thermal Plan standard. The sensors collected data on temperature, size and depth of the dispersed MLPP plume under varying tidal and power operating conditions (Duke 2000). Selected results from the Duke study are presented in Table 5. The long-term temperature recording stations represent distinct sampling regimes, within the vicinity of the discharge, the Elkhorn Slough itself, and a location on the adjacent beach. Temperature in the vicinty of the MLPP plume was recorded near the surface and at a depth of 10 feet (0.3 meters). In the slough, temperature measurements were taken on the north side of Highway 1 bridge at both 60 cm and 1.8 m below the surface. Finally, measurements at the beach were taken in the vicinity of the former Sandholdt pier at 60 cm below the surface.

Table 5: Temperature statistics from selected recording station in the Duke (2000) outfall discharge study.

Station	Location	Min	Max	Mean	Range
ML11	discharge	9	21	14.1	12
ML11	discharge -10	7.8	19	12.6	11.2
ML02	slough -2	10.5	20.3	15.7	9.8
ML02	slough -6	10.5	20.2	15.6	9.7
ML10	beach -2	7.7	23.2	14.3	15.5

Between June and October 2002, Paduan (2003) deployed a similar array of temperature loggers and thermistor strings to again measure the distribution of heated waters discharged by the Modernized Moss Landing Power Plant in complinace with the Central Coast Regional Water Quality Control Board permit and the California Energy Commission certification requirements. Selected results from this study are presented in Table 6. The long-term temperature recording stations in the table represent distinct sampling regions, such as within the vicinity of the discharge (cc1200, cc1205 cc12p2), the Elkhorn Slough (cc1-cc4), at stations along the beach (cc21-25), and at an offshore reference station (cc1700, cc1710). During sampling the plant operated at maximum load conditions for 24 hours on August 19th and 20th. The plant also operated at maximum load conditions during daylight hours on the 21st and 22nd of August. During the rest of the sampling period the load conditions reflected market demand.

Table 6: Temperature statistics from selected recording station in the Paduan (2003) outfall discharge study.

Station	Location	Min	Max	Mean	St. Dev.	Range
cc1200	discharge	11.2	20.8	15.1	1.61	9.6
cc1205	discharge -5	11.1	20	15.3	1.57	8.9
cc12p2	discharge +2	9.3	18.2	13.6	1.57	8.9
cc1700	offshore	10.5	17.6	14.5	1.04	7.1
cc1710	offshore -10	9.8	17.1	13.9	1.37	7.3
cc21-25	beach +2	11.7	19.1	15	1.37	7.4
cc01-04	ES plume	11.4	19.4	15.2	1.37	8

Temperature in the vicinity of the MLPP plume was sampled at the surface (cc1200), at a depth of five feet (1.5 m) (cc1205) and at two feet (0.61 m) off of the bottom (cc12p2). Temperature at the offshore stations were measured at the surface and at a depth of 10 feet (3 m). Subsurface stations measuring water temperature in the slough (cc01-04) were placed on the Highway 1 bridge and spread out across the main channel. All stations were averaged to give representative statistics for the slough. Similarly, the five stations at the beach (cc21-25), which measured temperatures two feet from the bottom, were averaged to give representative statistics for the beach.

The temperature measurements from both of these studies generally agree except for the recordings of beach temperatures, which may be due to the fact that the Duke (2000) study only had one beach station approximately 305 m from the MLPP outfall plume. The beach temperature loggers in the Paduan (2003) study were more representative of the entire stretch of beach and covered the entire area from the harbor entrace jetty to the former Sandholdt pier. These locations are, on the whole, closer to the MLPP plume than the single sensor used by Duke (2000).

There are five main points suggested by the time series data collectde by these studies: 1) strong mixing with ambient ocean waters reduces the maximum temperature elevations from the MLPP plume to less than several degrees Fahrenheit above ambient within a few hundered feet of the discharge location; 2) MLPP plume distribution is biased toward the inshore side of the discharge; 3) natural tidal exchange processes dominate temperature variability in the area, however the MLPP plume does affect water conditions surrounding the discharge site, particularly those immediately surrounding the discharge and the adjacent shoreline; 4) coastal sites beginning with the south breakwater and continuing southward along the coast (often extending more tha 200 feet southward) to the location of the former Sandholdt pier all show clearly skewed temperature anomaly distributions with a preponderance of temperature anomalies in the range of 1-4°F (0.6-2.2°C); and 5) anomalies greater than 4°F (2.2°C) at the shoreline or at 305 meters from the discharge site are rare, and certainly less than 50 percent of the duration of any complete tidal cycle.

Time series of temperature at selected stations (as described above) from the Paduan (2003) study are shown in Figure 9. Original data are represented as black dots with a cubic spline interpretation of these points plotted as a red line over the original points. All sites show temperature variation as a result of the influence of tidal mixing. Paudan (2003) also plotted power spectra that show clear evidence of processes taking place at dominant tidal frequencies (around once every 12 hours) and also at the diurnal

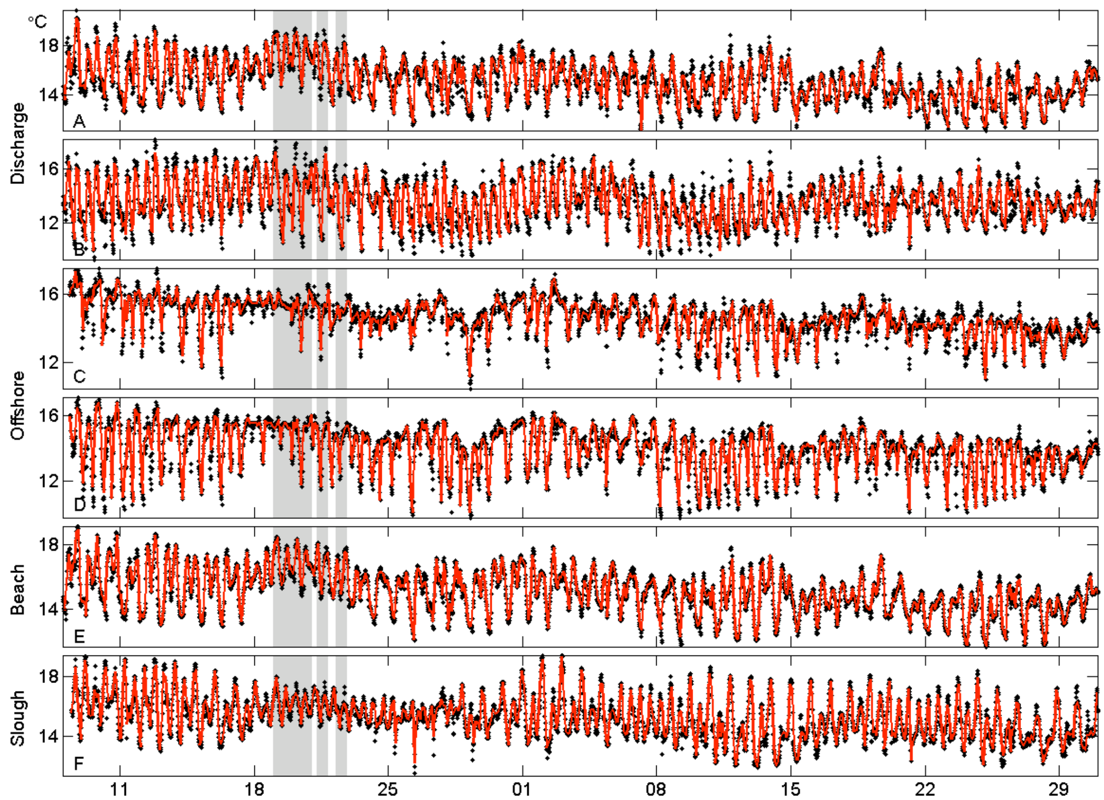

Figure 9: Temperature time series of selected stations from Paduan (2003) from August 8, 2002 to October 1, 2002; A) station cc12 in the vicinity of the discharge at the surface, B) station cc12 in the vicinity of the discharge two feet from the bottom, C) offshore station cc17 at the surface, D) offshore station cc17 ten feet below the surface, E) average of beach stations cc21 through cc25 recording at 2 feet from the bottom, F) the average of Elkhorn Slough highway 1 bridge stations cc01-cc03 at the surface. The grey boxes represent periods when the MLPP was operating at maximum capacity.

frequency (once every 24 hours). The diurnal fluctuations result from a combination of diurnal tidal fluctuations and diurnal solar heating. Measurements taken in the vicintiy of the discharge (cc12) show cooler temperatures at depth yet still above ambient conditions as measured at the offshore station (cc17). There also appears to be greater variability in temperature at depth. A slight increase in surface temperature was noted at the discharge site while the plant was operating at high thermal load discharge. This slight increase in overall temperature was also evident at beach stations, but not as evident in the plot at the offshore stations and in the slough.

Due to the apprent complexity of this time series data and the apparent influence of tidal fluctuations and thermal loading from the power plant, Paduan (2003) further examined temperature variability at several logging stations and its correlation to MLPP load. His results indicate that the correlation between the surface temperature of the MLPP plume and MLPP load increases with proximity to the MLPP discharge location, and particulary for those stations inshore of the MLPP discharge. There is also no lag in variation between the plume temperature and power plant load. With depth, however, this pattern diminishes. Near the bottom, the correlation between plume temperature (at depth) and MLPP loading decreases significantly, indicating that the MLPP discharge creates a bouyant plume and has little interaction with the bottom until it reaches the adjacent shore, where the anthropogenically warmed waters mix in the surf zone and act to increase temperatures locally. Further, statistical analyses of horizontal temperature gradients by Paduan (2003) indicate that the MLPP plume was moved around by tidal currents.

In order to reference ambient ocean temperature to the temperature of the MLPP plume and surrounding locations, Paduan (2003) used a temperature recorder attached to buoy cc17 (see Figure 2). The temperature recorded at cc17 compared reasonably well to temperatures recorded at the M1 time series station, 5 km west of the mouth of the slough. The nearshore station M0 had not been deployed at the time this study was conducted. Mean temperatures at cc17 and M1 during the MLPP thermal discharge study were 14.5°C and 13.8°C, respectively. At each of the stations, temperature ranged between 10.5 and 17.6°C at cc17 and 11.76 and 16.03°C at M1 for the period between August 9 and October 8, 2002.

Table 7: Mean temperature from fixed logger stations (Paduan 2003) in the slough, along the beach and near the discharge, along with the difference in temperature from each of the loggers at these sites relative to the ocean-reference station (cc17).

Station	**Location**	**Average Temperature°C**	**ΔT°C**
cc1200	discharge	15.10	+0.55
cc21	beach	15.03	+0.48
cc22	beach	14.97	+0.42
cc23	beach	15.02	+0.47
cc24	beach	15.03	+0.48
cc25	beach	15.03	+0.48
cc01	slough	15.08	+0.53
cc02	slough	15.15	+0.60
cc03	slough	14.98	+0.43

To understand the temperature change with respect to distance from the MLPP outfall, the mean time series records of selected stations were subtracted from the mean temperature recorded at cc17. The mean temperature at cc17 was 14.55°C at the surface and 13.9°C three meters below the surface. Only surface data are examined due to the mismatch in logger depth between stations. The results are presented in Table 7. On average temperature difference between outfall and neashore waters was ~0.5°C the difference ranged from ~3.7°C cooler to ~ 6.4°C warmer. Average temperature did not vary significantly between sites and average temperatures were actually slightly warmer in the slough, as opposed to the MLPP outfall site.

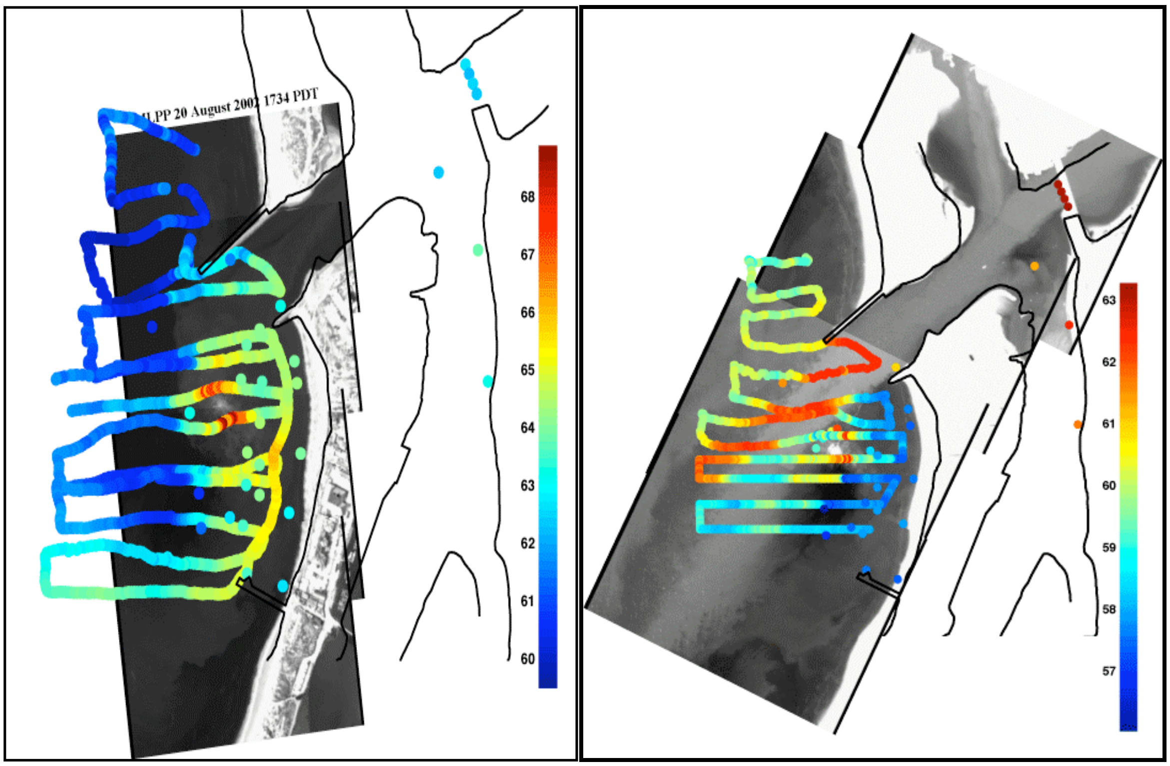

Figure 10: Results from Paduan (2003) shows an IR image during the flood tide (lighter shades are warmer) with near-surface temperature measured by the boat and buoy temperatures averaged over the time period of the boat survey (left). An IR image with survey and buoy data during the ebb tide (right).

3.3 Plume Comparison

3.3.1 Structure

Spatial data that represent single snapshots in time were also used to clarify the complex time series data and to compare the ES and MLPP plume structures. Additional sampling by boat and airborne sensor further defined the temperature distribution of the MLPP plume. These snapshots, presented in Paduan (2003), show that on the flood tide there is no clear distinction between the MLPP thermal plume and the ES plume (Figure 10, left). This suggests that the plumes may combine on a flood tide and the tidal forcing may move some of the outfall water northward toward the entrance of the harbor channel, while the coastal current continues to move some of the MLPP plume southward. On the ebb tide, however, the snapshots show a distinct and warmer ES plume exiting the harbor entrance in a southwesterly direction, while the MLPP plume appears to spread shoreward and southward, driven by the prevailing longshore current (Figure 10, right). Tidal inertia seems to dominate the movement of the ES plume through the southerly flow of the alongshore current.

Figure 11 shows data from boat surveys conducted on both an ebb (October 7, 2002) and flood tide (October 8, 2002). Collected to complement the airborne surveys in Figure 10,

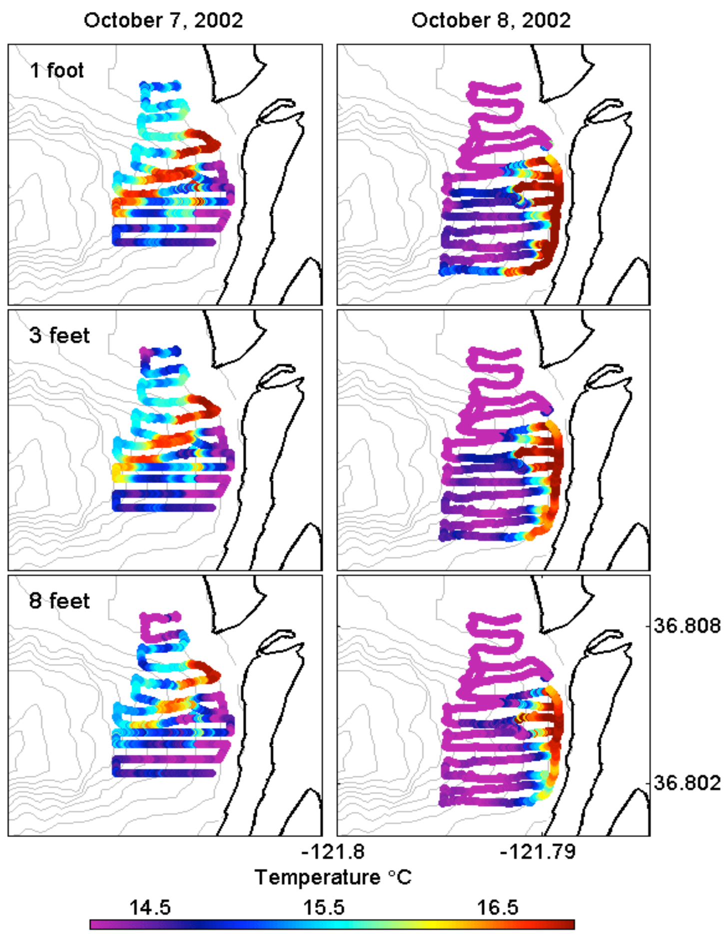

Figure 11: Temperatures measured from the survey boat in the Paduan (2003) study at near the surface, 3 feet and 8 feet in depth.

these surveys show that elevated temperature from the outflowing warm water from the Elkhorn Slough extends up to 8 feet in depth, and similarly, the influence of elevated temperatures from the MLPP plume also extend to 8 feet in depth inshore of the discharge. The contrast between flood and ebb tide conditions can be seen again in these surveys, with distinct plumes forming in the ebb tide and the MLPP thermal plume dominating the flood tide, especially shoreward of the outfall.

3.3.2 Thermal Contribution

Due to the high variability of temperature differences within the data and the different times of year and oceanographic regimes during which the data were collected, comparison between these two datasets can be difficult. One method of comparing the the thermal contribution and inferring the difference of measured temperatures can be to calculate the daily contribution of heat (calories) to the coastal ocean from each of these plumes using:

$$C = F x T_{diff} x Cal$$

where C (calories) can be found by calculating the product of daily water flow (F) or contribution from the source to the coastal ocean, temperature difference (T_{diff}) between plume waters and ambient neashore waters, and (Cal) (1.0 x 10^6), the amount of calories per cubic meter of water per change in one degree celcius. For the Elkhorn slough F is measured in terms of the tidal prism (6.7 x 10^6 m^3) (Laurence Breaker, pers comm). Assuming that 1.5 tidal prisms leave the Elkhorn Slough each day this translates to a sum of 10.05 x 10^6 m^3 of water flowing into the coastal ocean daily. Using (T_{diff}) between the lower slough (L01) and nearshore (M0) waters during June 1, 2004 and Feburary 23, 2005 we can reasonably estimate the contribution of heat to the coastal ocean. This occurs on the order of 7.4 x 10^{12} calories per day in extra heat coming from the ES plume.

The heat contribution from the MLPP plume (with the plant operating at full capacity) was calculated as 6.9 x 10^6 calories. Under these conditions the MLPP has an F, or maximum discharge of 850,000 gallons per minute or 4.6 x 10 m^3 per day. If we assume that the average daily temperature at the discharge site is 0.5°C above ambient temperature (T_{diff}) (Table 7), then the total amount of heat contributed from MLPP discharge to the coastal ocean is 2.3 x 10^{12} calories per day.

4. Summary and Discussion

The Elkhorn Slough plume is a surface advected plume dominated by tidal interia. Based on observations, the ES plume typically extends on an ebb tide in a southwesterly direction, extending approximately one kilometer into the coastal ocean, reaching a width of approximately 500 m. Calcualtions of the inertial radius of the plume, based on current speed, indicate that the inertial influence may extend up to ~8 km offshore (Geyer et al., 2000). Vertical profiles show that plume depth can range between 5-10 meters and this is supported by calculations of the plume lift-off depth, which estimate a plume thickness of 12.28 m. Portions of ES plume waters may be entrained in the northward flowing bay waters as indicated by drifter movement.

By contrast the MLPP outfall plume is injected vertically through the water column, and is frequently seen breaking the sea surface directly over the discharge site. At the surface, the MLPP outfall plume is biased toward the inshore side of the discharge, most commonly occupies the region between the discharge site and the edge of the surf zone, and often extends more than 61 m southward along the adjacent coast. The MLPP plume often exceeds 2.5 m in thickness, but rarely has contact with the bottom, except in the surface zone where MLPP plume waters are mixed by wave action.

The ES and MLPP plumes appear to interact through tidal processes. On the ebb tide, the ES plume's high tidal inertia dominates the nearshore environment and creates distinct frontal regions eminating in a southwesterly direction. The MLPP plume is retained shoreward of this frontal region and shows distinct structure that flows shoreward and south of the discharge site, influenced slightly by along-shore flow. On the flood tide the ES and MLPP plumes combine and appear to flow toward the harbor entrance.

The results and previous studies have shown that temperature of both the ES and MLPP plumes are highly variable and are influenced significantly by tidal mixing. Other factors, such as upwelling at the canyon head and mixing between plumes may also influence temperature variability. Based on daily averages, the ES plume upon exiting the slough was generally warmer than the surrounding ambient ocean water, though throughout the winter months these average daily tempertures at ebb tide varied from ~1.3 cooler to 2.3°C warmer than surrounding ambient ocean water. Overall, temperature differences between the average ES plume waters versus ocean waters were generally <1°C.

Comparison of temperature time series reflect regional extremes within the slough, with the upper slough responding more closely to changes in air temperature, due mainly to reduced tidal mixing and increased radiative absorption and emission in shallow, less dynamic waters. Temperature in the lower portion of the slough more closely reflect temperature variability in the ocean due to tidal mixing with oceanic waters. Extreme temperature differences between the outgoing ES plume and ambient oceanic waters are more likely to occur during the spring tides when tidal exchange reaches the upper slough.

The average MLPP plume temperature during the Paudan (2003) study was warmer than the surrounding waters when compared to the temperatures recorded at the ocean reference site. Though the variability of temperature measured at the MLPP discharge site differed from the reference site by ~3.7°C cooler to ~ 6.4°C warmer, the overall average temperature at the discharge site was ~0.5°C warmer than the surrounding oceanic water. The recordings of cooler temperatures at the MLPP discharge site occurred only 15% of the time during the sampling period. Temperatures in the slough were cooler than surrounding nearshore oceanic waters 20% of the time.

The thermal contribution from both the ES appears to be about 3 times greater than the MLPP ouput. However, several assumptions have been made when carrying ou this calculation. It was assumed that the MLPP plant operates at maximum capacity 24 hours per day. In reality, the plant operates under market demand (i.e. it does not operate at maximum capacity 24 hr per day), so the value of thermal discharge of the MLPP is an overestimate and represents a worst-case scenario. We also used the average temperature difference between MLPP discharge and ambient waters which incorporates the influences of tidal mixing and may reduce the overall estimate (i.e. making the estimate too conservative). Similary, a full year of average daily temperature differences between the MLPP plume and neashore waters was not available. The daily average contribution of heat to the coastal ocean is based only on data during June to February. However, should additional data become available it is not expected that the relative heat contribution would be significantly different than currently calculated.

4.1 Future research

The comparison of two plumes from disparate datasets can be, at best, difficult. Each of the datasets in this study were collected for different purposes and the studies were conducted during different seasons. This introduced different sources of variability to each of the datasets due to the varying climatic and oceanographic conditions in the study area. Additionally the area sampled is an extremely dyanmic area, influenced by not just the ES and MLPP plume, but also tidal processes interacting at the canyon head, along shore currents, and bay-wide circulation patterns. Temperature variability has numerous components within the coastal zone and portraying the varibilty of one of these components can be difficult with a limited amount of concurrent data on all components.

Further research is required in order to fill the gaps in our understanding. The most important component of this equation would be to gain a better understanding of flux of water and material leaving both the ES and the MLPP outfall. Similary, it is important to understand the flux of water entering ES. The flux at the outfall pipe should also be measured on a continual basis to establish a firmer understanding of the correlation between thermal load and market demand. Flux studies of ES can be conducted by the installation of an ADCP current meter in the main channel, or less expensive field based efforts involving students at Moss Landing Marine Laboratories (MLML). Drifter deployment at the mouth of ES would be the first step toward understanding the process of flow into ES. Drifter deployment would be easily conducted with the existing materials from the original ES plume study and through coordination between staff at MLML and MBARI. Additional questions to consider are: 1) What are plume responses to wind events? Does the MLPP plume typically stay inshore of the outfall location, or can the warm waters from the outfall disperse seaward, when the strong frontal zones created by ES do not prevent this movement?

Most importantly, however, is the need to obtain a more robust comparison of the ES and MLPP plumes. This requires a coordinated collection of data sets, examining both the ES plume and MLPP plume simultaneouly, spanning a complete tidal cycle, and during different seasons and oceanographic regimes in Monterey Bay. A continual sampling mechanism such as repeated visible and thermal remote sensing during a complete tidal cycle during different climatic, oceanographic and tidal regimes will be invaluable in understanding both the dynamics of plume interaction and their temperature dispersion. Remote sensing overflights should be coordinated with the CIRPAS facility at the Naval Postgraduate School or the Unmanned Aerial Vehicle Applications Center, a collaboration between NASA and Clark University, based at the NASA Ames Research Center.

Further understanding of temperature variability within Elkhorn Slough can be gained by examining data from the series of LOBO moorings in the slough and how temperatures change through tidal, diurnal, and seasonal cycles. Correlations of temperature with rain events and salinity are also important to understand because of the stratification that may be introduced by less saline and buoyant waters. During the rainy winter months fresh cool water may enter the slough and change the density and salinity of slough waters and produce a surface advected plume as was measured during this plume study. However, during summer months when the rainfall ceases, freshwater input is minimal and a highly saline, inversely stratified estuary may form. To further understand the dynamics and structure of the ES plume, it would be important to further understand salinity changes in the slough, stratification and the interaction of water layers with the mixing processes at the canyon head in comparison to the thickness and advection depth of the plume.

Due to the highly variable nature of plume temperatures, other parameters maybe a better indication of the ultimate fate, structure and dynamics of both of the plumes. Other physical, chemical and biological data from the Elkhorn Slough plume study were not completely examined here, but could be examined further to understand the extent to which the ES plume influnces coastal waters. For example, the following questions could be examined further: 1) What is the fate of sediment in the plume? 2) Are the sediments deposited into the canyon or transported to the north bay as the drifter suggests. Also, sediment, CDOM fluorescence and nitrates seem to be the parameters that most clearly describe the ES plume. Do other physical, chemical or biological parameters distinguish outfall waters from ambient waters more clearly than temperature? For example, an analysis of nitrate would be interesting, considering that the slough has high concentrations of nutrients in the vicinty of the intake for the power plant. Furthermore, fatty acid analysis might prove useful to differentiate water masses by distinguishing between the relative concentrations of bacteria, terrestrial matter and phytoplankton. Finally, could any of these parameters be used to understand the mixing of different parcels of waters as each of the plumes enters the coastal ocean?

The data presented here are beginning to shed some light on the process contributing to temperature variability in the vicinity of the Moss Landing harbor mouth where influences of a thermal discharge from an anthropogenic point source can be compared to that of the natural heat flux between two natural bodies of water, an estuary and the open ocean. Preliminary data describe the general flow and structure of both the Elkhorn Slough and MLPP plumes and the thermal contribution from each of these plumes to the coastal ocean.

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