OCEANOGRAPHIC STUDIES USING AVIRIS IN MONTEREY BAY, CALIFORNIA

Andrew M. Fischer,[1] John P. Ryan,[1] Erich V. Rienecker,[1] Patrick McEnaney,[1]
Laurence C. Breaker,[2] Nicholas A. Welschmeyer[2]

1. Introduction

The coastal waters of Monterey Bay (Figure 1) are dynamic and complex. Ocean processes at multiple temporal and spatial scales influence the distribution and abundance of phytoplankton and marine life. These processes range from the large-scale influences of the California Current, to mesoscale eddies and filaments and small-scale frontal dynamics. Human activities on land (agriculture, urban development and waste treatment) can also influence the ecology of Monterey Bay. Estuarine and riverine plumes can carry land-based sources of pollutants and nutrients into coastal waters. Several of these processes occur at scales greater than that covered by in situ measurements, and often cannot be resolved by techniques of satellite remote sensing, which cover large areas at relatively coarse resolution (~1 km). Therefore, it is critical to use new techniques, at appropriate scales, to fill these gaps in observations. Ultimately, multidisciplinary studies requiring sampling across these scales are needed in order to understand how these processes influence the ecology of Monterey Bay.

Recent acquisitions by the Airborne Visible Infrared Imaging Spectrometer (AVIRIS) over Monterey Bay have begun to close these gaps in observations. AVIRIS, coupled with in situ measurements and multidisciplinary, multi-sensor analyses, have revealed small-scale ocean processes and phenomena important to understanding bay ecology. These processes relate to red tide development and estuarine plumes.

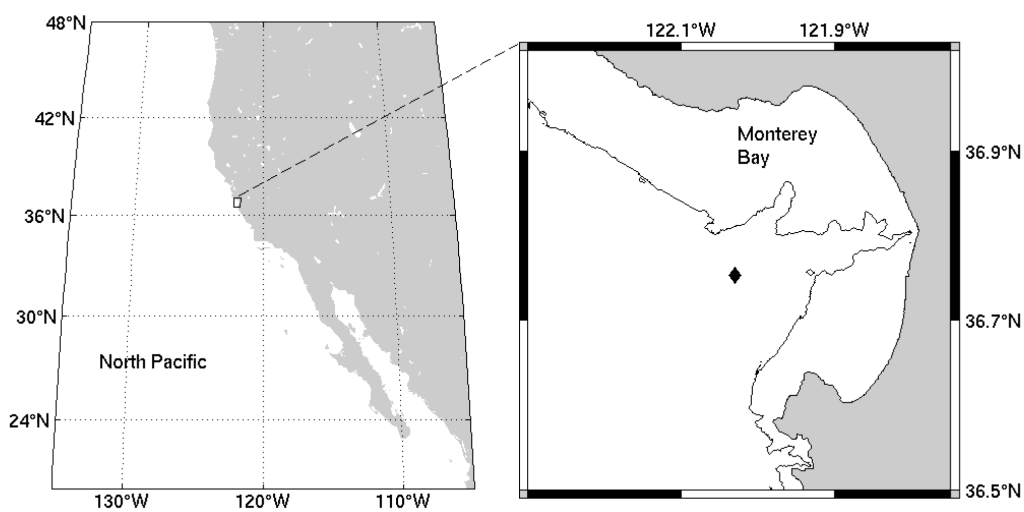

Figure 1: Monterey Bay, located on the central coast of California, is known for its productive marine waters and diverse marine life. The time-series oceanographic research station (M1) is located in the center of the Bay (diamond).

[1] Monterey Bay Aquarium Research Institute, Moss Landing, California (afischer@mbari.org)
[2] Moss Landing Marine Laboratories, Moss Landing, California

1.1 Red tide

Red tide blooms in coastal ocean environments have substantial economic consequences primarily through introduction of toxins into the food web and generation of hypoxic or anoxic conditions during bloom decay (Shimizu, 1989; Horner et al., 1997; Smayda, 2000; Hoagland et al., 2002). These blooms are termed red tides because their dense accumulations of microscopic algae cause ruddy discoloration of near surface waters. Red tides that have deleterious consequences are termed harmful algal blooms (HABs). Because of their substantial impacts, red tides and HABs are important phenomena to detect and predict, and their complexity necessitates observing and modeling systems that integrate diverse scales and methods of sensing. Here we report progress on a red tide study employing AVIRIS as a key observational asset within an observing system array that included satellites, aircraft, ships, mooring and microscope. With this array we closely observed genesis and evolution of a red tide in Monterey Bay to reveal complex processes forcing the genesis and evolution of the event.

1.2 Elkhorn Slough plume

The Elkhorn Slough is a significant year round link between land use activities and the coastal waters of Monterey Bay. Agricultural runoff, collected in the slough during periods of precipitation, can be carried, by means of tidal exchange, into Monterey Bay. Tidal scouring of the banks and bed of the slough, can resuspend pollutants that have accumulated in sediments over the past several decades. Increased flux of nutrients and pollutants into the Bay can influence water quality, increase the prevalence of harmful algal blooms and marine diseases, and have consequences for nearshore ecology.

This exchange is of particular concern because its physical configuration has been drastically altered by human intervention. In 1946, the Army Corps of Engineers changed the morphology of Elkhorn Slough by cutting through the dune barrier separating the slough from Monterey Bay. Since then, the slough has been transformed from a sluggish backwater to a shallow, tidally forced embayment. Maximum tidal currents in the main channel of the slough have increased from approximately 1.5 knots in 1971 to 3.0 knots today, and the tidal prism, the volume of water that is exchanged between the slough and the bay over a tidal cycle, has increased by 43 percent during the last decade.[3] As the tidal currents and tidal prism continue to increase, and the surrounding watershed is subject to growing population pressures and land use change, there is a need to understand the physical extent and the biological impacts of the plume of water entering the bay from the slough.

Recent measurements have revealed components of the physical and biological exchange between the Elkhorn slough and Monterey Bay. Here we have combined in situ measurements with AVIRIS hyperspectral imagery to begin to understand the constituents of the slough plume, their transport and fate.

---

[3] Breaker et al., In Prep

2. Methods

2.1 Red Tide

2.1.1 AVIRIS

AVIRIS was flown on the high altitude ER-2 platform over Monterey Bay on October 7, 2002. The bay and adjacent waters were imaged in 51 minutes with four swaths, each 11 km wide and overlapping by ~1 km. Flight line orientation was optimized relative to local sun angle during the acquisition period. These data were atmospherically corrected using Tafkaa atmospheric correction software (Montes, 2004; Gao et al., 2000). Aerosol model parameters (tau 550 and relative humidity) for the Tafkaa input files were derived from **Sea**-viewing **Wi**de **F**ield-of-view **S**ensor (SeaWiFS) ancillary products. The SeaWiFS satellite collected data over Monterey Bay within 26 minutes of AVIRIS flight time. Chlorophyll concentrations were computed using the same algorithm that is used for SeaWiFS satellite imagery (O'Reilly et al., 1998).

2.2 Elkhorn Slough plume

2.2.1 AVIRIS

AVIRIS imagery from the high-altitude ER-2 platform was collected over Monterey Bay on October 13, 2000 and October 7, 2002. A discharge plume was observed exiting the mouth of the Elkhorn slough (Figure 2a & 2b). This tidal discharge interacts with alongshore currents and subsurface topography, to create a complex region of frontal zones (Figure 2c). Observation of this plume within the AVIRIS imagery, highlighted a phenomenon of estuarine/oceanic exchange that has until now been overlooked by researchers in Monterey Bay.

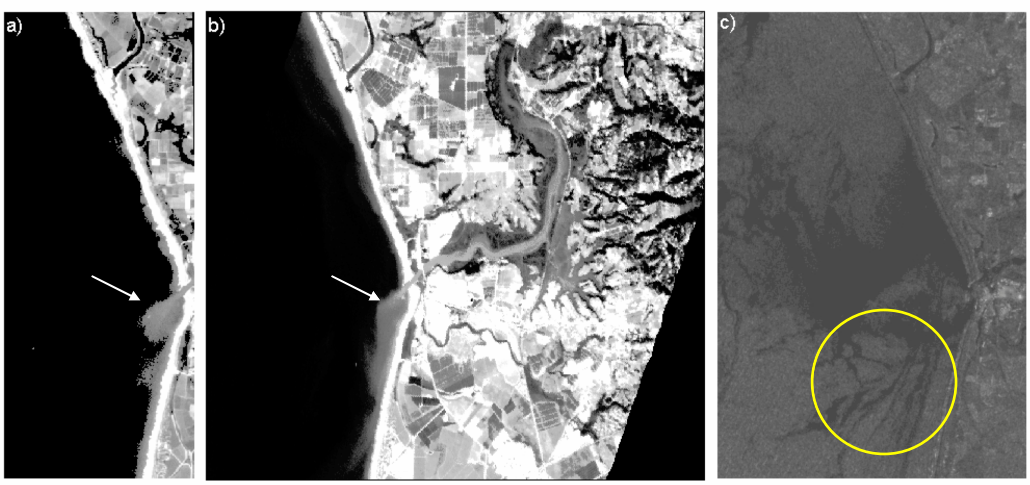

Figure 2: a) An enhanced gray-scale image, derived from hyperspectral imagery collected by the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) on October 13, 2000, reveals a discharge plume exiting the mouth of the slough. b) AVIRIS captured this same feature during an overflight on October 7, 2002. c) Multiple narrow frontal zones (within yellow circle) are evident in imagery captured by synthetic aperture radar, revealing complex interactions between the slough plume and canyon upwelling.

The AVIRIS observations launched a series of in situ measurement efforts described below. Further analysis of AVIRIS imagery was conducted to begin to understand this exchange. AVIRIS imagery was atmospherically corrected as in 2.1.1. The appropriate flight lines from the AVIRIS mission were subset to encompass the slough and the surrounding nearshore waters of Monterey Bay. The methods employed by Kruse et al. (1997), were then used to classify the nearshore water types of the slough, plume and coastal ocean. This preliminary procedure was carried out in order understand spectral differences in potential water types classes and aid in understanding the fate of the plume class and interaction of slough/plume with the oceanic classes. The procedure consists of 4 steps. First is the application of a "minimum noise fraction" (MNF) transform to the atmospherically corrected image. This procedure is used to reduce the number of spectral dimensions to be analyzed. The MNF transform orders the data according to the signal-to-noise ratio and reduced redundancy by selecting out bands, which contain the most information (Green et al., 1988). Second, is the application of the pixel purity index (PPI) algorithm, to determine pure endmember spectra. Finally, the spectral angle mapper (SAM) classification procedure, using image derived endmembers, produced reasonable classes distinguishing, slough, plume and oceanic waters.

2.2.2 In situ Observations

The plume exiting the slough was characterized by in situ observations on several occasions from the R/V Zephyr. These measurements were not concurrent with the AVIRIS overflight, but were collected in subsequent field operations. A continuous underway-mapping system collected sea surface parameters of temperature, salinity, color dissolved organic matter (CDOM) and chlorophyll fluorescence, transmission (a proxy for turbidity), and nitrate. Water samples and CTD profiles were collected at six successive sampling stations with increasing distance seaward of the slough. Water samples were analyzed for chlorophyll and carotenoids, naturally occurring plant pigments, and fatty acid content. Data were collected at the lowest stage of the ebb tide, when the extent of the plume is most prominent.

3. Results

3.1 Red Tide

At the time of this writing we are preparing to submit this red tide study for review by *Science*. To avoid potential copyright concerns we present here only a brief summary to highlight the key contribution made by AVIRIS in this multidisciplinary study. Satellite ocean color observations, mooring observations, and *in situ* surveys of Monterey Bay illustrated dramatic short-term changes in the physical and biological environment preceding a red tide. Specifically, the bay was flushed by an intrusion of offshore waters, after which a red tide bloom rapidly formed throughout most of the bay. Between the ~1 km x 1 km pixel of the satellite and the periodic synoptic maps of the ocean interior by towed undulating vehicle, the very high resolution synoptic remote sensing by AVIRIS contributed a key finding about the creation of highly concentrated red tide patches by physical processes. In this aspect of the study, we combined surface chlorophyll concentrations estimated from AVIRIS with same-day imaging of the bay by synthetic aperture radar (SAR). This combination of physical and bio-optical remote sensing, a first in coastal ocean studies, revealed the alignment of the most highly concentrated red tide patches in convergence zones created by internal waves.

3.2 Elkhorn Slough plume

Several sea surface parameters were collected by the underway-mapping system (Figure 3) revealing complex interaction between plume waters and upwelled water from the Monterey Bay submarine canyon. The slough water, identified by salinity, was primarily in two narrow bands following the canyon shelf break. A high nutrient (nitrate) signal, coincident with warm temperature and low salinity, was associated with the plume only very close to the source (within ~50 m). Seaward of this there was also a high nitrate signal aligned with a cold, salty anomaly. This supports a source from subsurface ocean (vertical mixing or upwelling). Although the slough plume had lower mean transmission (higher turbidity) than the offshore surface oceanic water, the maximum in turbidity was not in the slough plume. Instead it was in the upwelled canyon head-waters, identified by salinity and temperature.

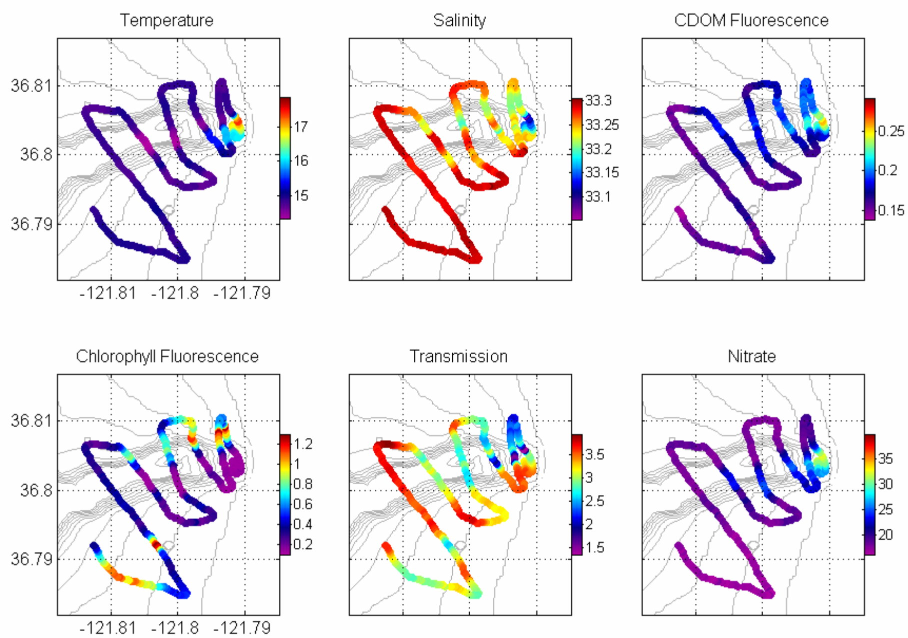

Figure 3: Underway-mapping results show complex interactions between plume and oceanic waters, influenced by upwelled waters at the head of the Monterey submarine canyon. The underway results are plotted over canyon bathymetric contours (light gray).

The plume's physical characteristics, depicted through ship-based profiles, show a wedge of warmer less saline water exiting the slough at maximum ebb tide, producing a sharp salinity gradient (halocline) where slough waters meet oceanic waters (Figure 4a). The resulting density gradient (pycnocline) enhances stratification, isolates plume waters from oceanic waters below, suppresses vertical mixing, and makes conditions potentially favorable for phytoplankton growth and harmful algal blooms.

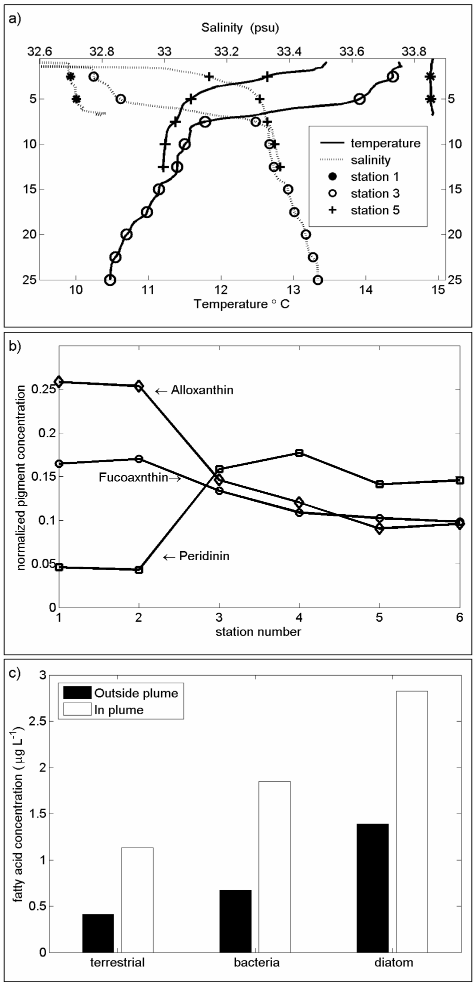

Figure 4: a) Temperature and salinity profiles of the plume show a low-salinity cool mass of water exiting the slough on low tide. The dotted lines are salinity and the solid lines are temperature. The solid circles indicate measurements taken inside the harbor entrance (station 1), the open circle just outside mouth of the harbor (station 3) and, and plus symbol indicates a sample taken at the 70-meter isobath (station 5). b) Fucoxanthin, alloxanthin and peridinin pigment concentrations retrieved from water samples. c) Fatty acid concentrations of terrestrial matter, bacteria and diatoms averaged among the 6 stations (white bar) and compared with and a control sample of oceanic water (dark bar).

Water samples, collected in successive sampling stations with increasing distance seaward of the slough, reveal distinct assemblages of phytoplankton between plume and bay waters. Analyses of these samples show high concentrations of alloxanthin, a carotenoid found in the phytoplankton group *Cryptophyta*, dominating the inland waters of Elkhorn slough (Figure 4b). Further from shore, alloxanthin concentrations diminish and concentrations of peridinin, a pigment indicative of the phytoplankton group *Dinoflagellata*, increase. It is possible that a plume of inland slough water, on a low enough tide, can introduce rich concentrations of cryptophytes into the bay influencing food web dynamics and biogeochemical transformation rates.

The water samples were examined further using fatty acid biomarker analysis. Examination of specific fatty acids and different lipid classes will provide a better understanding of sources of input to plume waters. The results show that plume water carries indicators of terrestrial material, bacteria and diatoms. Fatty acid concentrations of each of these markers were more abundant than those sampled from a control sample taken from nearby oceanic waters (Figure 4c). The presence of terrestrial biomarkers indicates the transport of “foreign” or land-based materials into Monterey Bay.

The SAM classification results produced reasonable classes separating slough, plume and ocean waters (Figure 5a), confirming the presence of a plume of spectrally distinct water (as in the visible image) exiting the slough and entering Monterey Bay. The plume becomes entertained in the alongshore current and proceeds south along the shoreline. The mean spectra of the classes differ in magnitude throughout the spectrum (Figure 5b). The overall increase in brightness in the slough and plume spectra is most likely due to suspended solids and the resultant increase in scattering.

Suspended sediment concentrations derived from the AVIRIS imagery (Binding et al., 2003), show elevated sediment in plume surface waters, with the highest

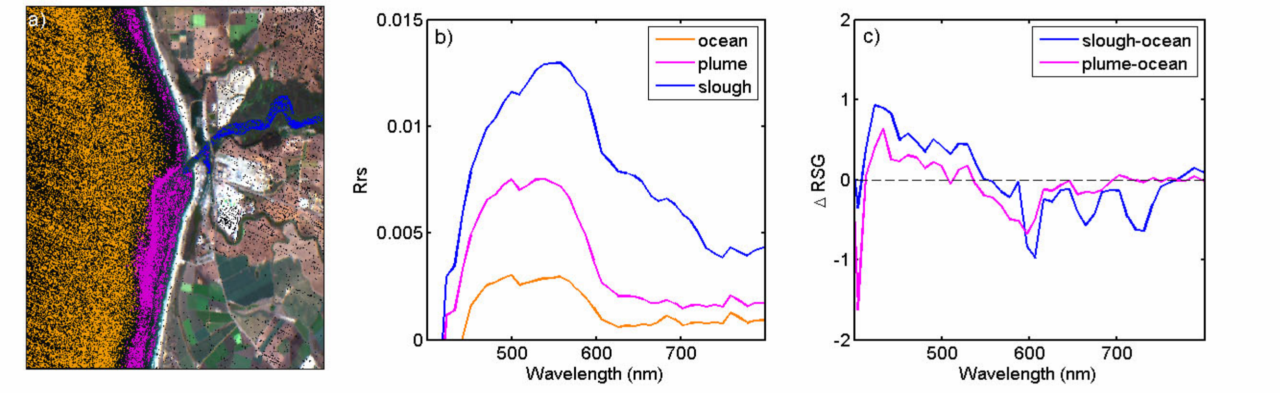

Figure 5: a) Spectral Angle Mapper classes for ocean (orange), plume (magenta) and slough (blue), b) class mean spectra, c) the first derivative of slough and plume classes referenced against the first derivative of the ocean class.

concentrations within the slough and at its mouth (Figure 6). Sediment loads vary between image dates, with ranges between 1 and 900 mg L^{-1} on October 13, 2000 and between 3-400 mg L^{-1} on October 7, 2002. This variability may be based on the rainfall, the stage and height of the tide and the degree of land use activity. The striking feature of these two images is that the suspended sediments quickly settle out of surface waters. The sediment particle size, sources and transport of eroded material from the banks and bottom of the slough should be examined further. Validation of the sediment algorithm results and field verification of sediment particle size distribution are currently being conducted.

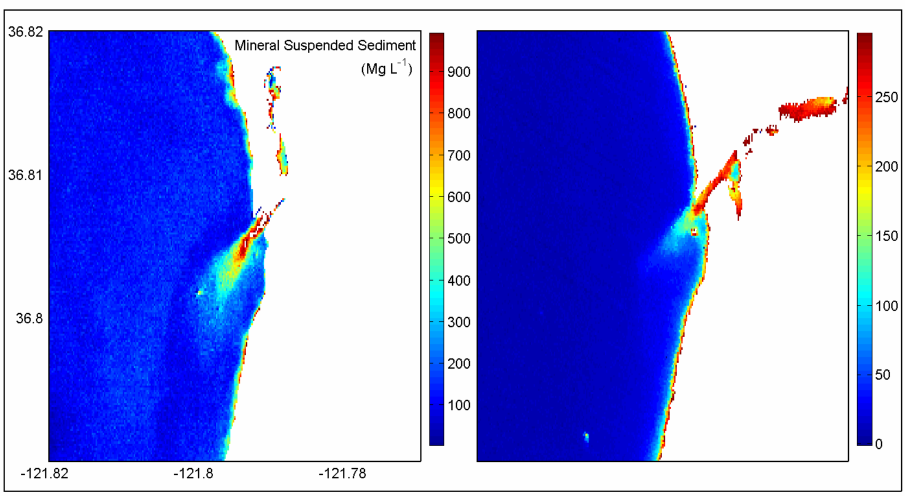

Figure 6: Mineral suspended sediments derived from the 2000 (left) and 2002 (right) AVIRIS captures of the slough plume.

Variations in magnitude and shape of the water type class spectra from the SAM classification results provide a useful framework for future algorithm development in plume studies. Mean raw spectra show subtle changes in slough spectral shape between 600 and 750 nm indicating subtle changes in variations of reflectance from plume and ocean spectra (Figure 5b). There is also a peak at approximately 645 nm in the slough spectra. To understand differences in spectral shape and further distinguish spectral differences between classes, first order derivative spectra were generated after mean-filter smoothing (filter size = 3 points). First derivatives of slough and plume spectra, referenced against oceanic spectra, share subtle variations in spectra at approximately 600 nm (Figure 5c). However, differences in reflectance between in the referenced slough and plume spectral derivatives appear at 660 and 730 nm. A spectral feature evident in the slough class has diminished once they have become a plume in the coastal ocean. Further examination to understand this variation in class spectra is currently being conducted.

4. Summary

AVIRIS imagery collected from the high altitude ER-2 platform has revealed small-scale processes in Monterey Bay, which play an important role in coastal ecology. The high-resolution AVIRIS imagery revealed convergence zones, created by internal-wave activity, which can concentrate potentially harmful red-tide organisms. The imagery also observed a coastal estuarine plume, which is potentially influencing the bay by introducing sediments, unique microbes and terrestrial matter. This sediment-laden plume creates complex interactions with upwelled waters from the head of the Monterey submarine canyon. Analyses of phytoplankton pigments show that cryptophytes, which dominate the inland waters of the slough, can be introduced into the Bay on spring tides, influencing ecology throughout the bay. Further analysis of fatty acid concentrations confirms the transport of terrestrial matter and bacteria into the bay. Heightened levels, or blooms of diatoms in the plume, may be a result of elevated levels of nutrients transported from the surrounding agricultural fields. Mean class spectra from the SAM classification procedure shows variability in spectra between slough, plume and bay waters. Spectral differences at 660 and 730 nm might form the basis for algorithm development to track slough or plume constituents throughout the bay via remote sensing. Finally, an application of sediment algorithms shows the rapid settling out of mineral suspended sediments in the plume.

5. Future Work

Dynamic ocean and estuarine processes in Monterey Bay present extremely difficult challenges in oceanographic sampling. Processes interacting at multiple spatial and temporal scales create a highly dynamic target, which can be difficult to resolve. AVIRIS overflights from 2000 and 2002 have bridged gaps in these scales and have been extremely valuable in identifying small-scale processes in Monterey Bay. We will continue multidisciplinary studies with AVIRIS imagery, combining in situ and multi-sensor analyses to sample across multiple temporal and spatial scales. Red tide development was observed during the most recent (2004) AVIRIS acquisition. This imagery will be critical for examining the development of this red tide event. Further spectral analysis of water class spectra will form the basis of algorithm development to derive inherent optical properties. Testing is now underway to validate and extract suspended sediment concentrations and color dissolved organic matter (CDOM). Particle–size spectrum analyses are being conducted to determine size, source and transport of sediments from the slough into the coastal ocean. AVIRIS will continue to provide us with a greater understanding of the influence of oceanographic and estuarine phenomena on the ecology of Monterey Bay.

6. References

Binding, C.E., D.G Bowers, E.G. Mithcelson-Jacob, 2003, "An algorithm for the retrieval of suspended sediment concentrations in the Irish Sea from SeaWiFS ocean colour satellite imagery." International Journal of Remote Sensing, vol. 24, no. 19, pp. 3791–3806.

Green, AA M. Berman, B. Switzer, M.D. Criag, 1998, "A transformation for ordering multispectral data in terms of image quality with implications for noise removal." IEEE Transactions on Geoscience and Remote Sensing, vol. 26, no. 1, pp. 65–74.

Hoagland, P., D. M. Anderson, Y. Kaoru, A. W. White, 2002, "The economic effects of harmful algal blooms in the United States: Estimates, assessment issues, and information needs *Estuaries*, vol. 25, no. 4B, pp. 819.

Horner, R.A., D. L. Garrison, F. G. Plumley, 1997, "Harmful algal blooms and red tide problems on the U.S west coast." *Limnology and Oceanography,* vol. 42, pp. 1076.

Gao, B.C., Montes, M. J., Ahmad, Z. & Davis, C. O., 2000, "Atmospheric correction algorithm for hyperspectral remote sensing of ocean color from space." *Applied Optics,* vol. 39, pp. 887.

Kruse, F.A., L.L. Richardson, V.G. Ambrosia, 1997, "Techniques for geological analysis of hyperspectral data applied to near-shore hyperspectral ocean data." Foruth International Conference on Remote Sensing for marine and Coastal Environments, Orlando, Florida, 17–19 March.

Montes, M.J., Geo, B.G & Davis, C.O., 2004, "NRL Atmospheric Correction Algorithms for Oceans: Tafkaa User's Guide." NRL/MR/7230-04-8760.

O'Reilly, J. E. et al., 1998, "Ocean color chlorophyll algorithms for SeaWiFS." *Journal of Geophysical Research,* vol*. C* 103, pp. 24937.

Shimizu, Y., in *Red Tides Biology, Environmental Science, and Toxicology: Proceedings 1st International Symposium on Red Tides,* T. Okaichi, D. M. Anderson, T. Nemoto, Eds. (Elsevier, New York, 1989), pp. 17–22.

Smayda ,T. J., 2000, "Ecological features of harmful algal blooms in coastal upwelling ecosystems." *South African Journal of Marine Science*, vol. 22, pp. 219.