Adaptive Sampling of Phytoplankton Responses to Episodic Physical
Forcing in the Nearshore Coastal Ocean

(NASA Presidential Early Career Award for Scientists and Engineers)

Final Technical Report

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Project Summary

The original proposal focused on the linkages between in-water physical, biological and optical dynamics and to assess the degree to which remote sensing could be applied. These areas were approached during the 2001 sampling season and with follow on studies, as part of the extension of the grant through the PECASE award, there are three specific areas of work that have evolved from these original efforts. The first is a further examination of the coherence between convergence zones, general current patterns and spatial distribution of in-water biological signals (phytoplankton). The second is a remote sensing focus, attempting to define the critical spatial scales for biology in the coastal environment and the third, which is related, is developing a new tool for *in situ* spatial validation of remotely sensed products. For clarity, this final technical report will begin with a general description of the sampling effort followed by results from these three areas and products produced by this project.

Sampling Approach

Adaptive sampling of phytoplankton responses to episodic physical forcing in the nearshore coastal ocean was assessed during the summer of 2001 using the Rutgers Long Term Ecosystem Observatory (LEO-15) network **(Fig. 1)**. LEO-15 is an existing observational network of satellites, aircraft, radar, autonomous nodes, research vessels and autonomous vehicles located and/or deployed off the New Jersey coast.
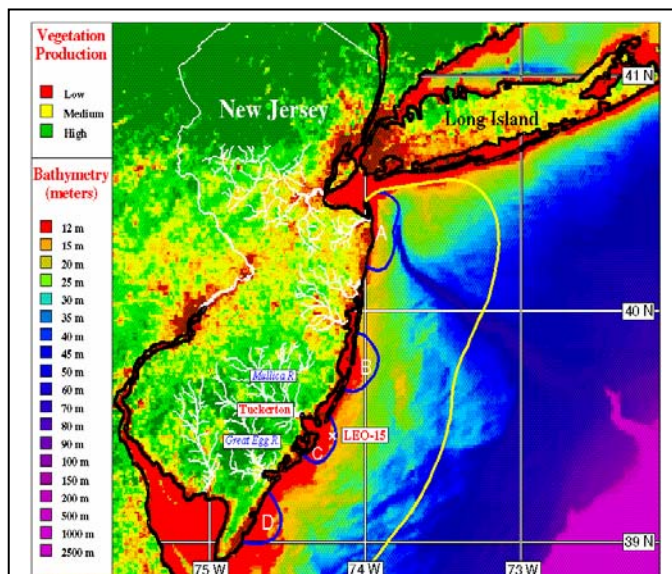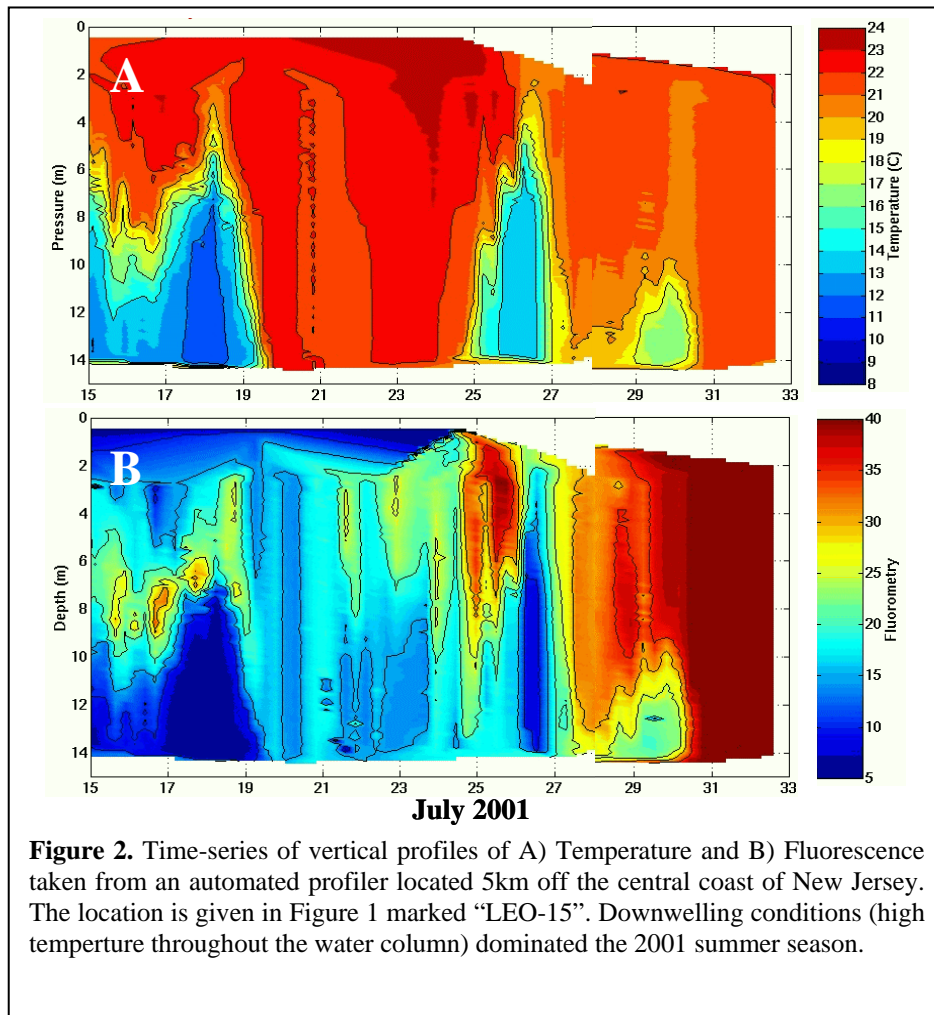

Figure 1. Experiments were conducted at the instrumented field site of the Long Term Ecosystem Observatory (LEO-15), located off the central coast of New Jersey.

Based on a six-year time series, the coast of New Jersey is traditionally characterized by intermittent upwelling. Upwelling begins as a uniform band of cold water along the coast. Interactions with the bottom initially cause a 2-dimensional front to evolve into a recurrent upwelling center located on the downstream sides of a seafloor topographic high directly off the Rutgers field station where the present work was conducted.

The recurrent upwelling center is separated from the warm offshore waters by a sharp (kilometer scale) upwelling front that is readily visible in Advanced Very High Resolution Radiometer (AVHRR) and Synthetic Aperture Radar (SAR) satellite imagery. The subsurface location of the frontal boundary is also clear in the in situ spectral signatures of the apparent optical properties (AOPs) and inherent optical properties (IOPs). While the upwelling center itself is typically about 25 km in diameter, it contains many observed features that occur at smaller scales. A strong alongshore jet

(20-30 cm/sec) remains on the warm side of the upwelling front above the thermocline as it meanders around the colder upwelling center. Consistently associated with the offshore thermocline is a broad chlorophyll peak.

Figure 2. Time-series of vertical profiles of A) Temperature and B) Fluorescence taken from an automated profiler located 5km off the central coast of New Jersey. The location is given in Figure 1 marked "LEO-15". Downwelling conditions (high temperture throughout the water column) dominated the 2001 summer season.
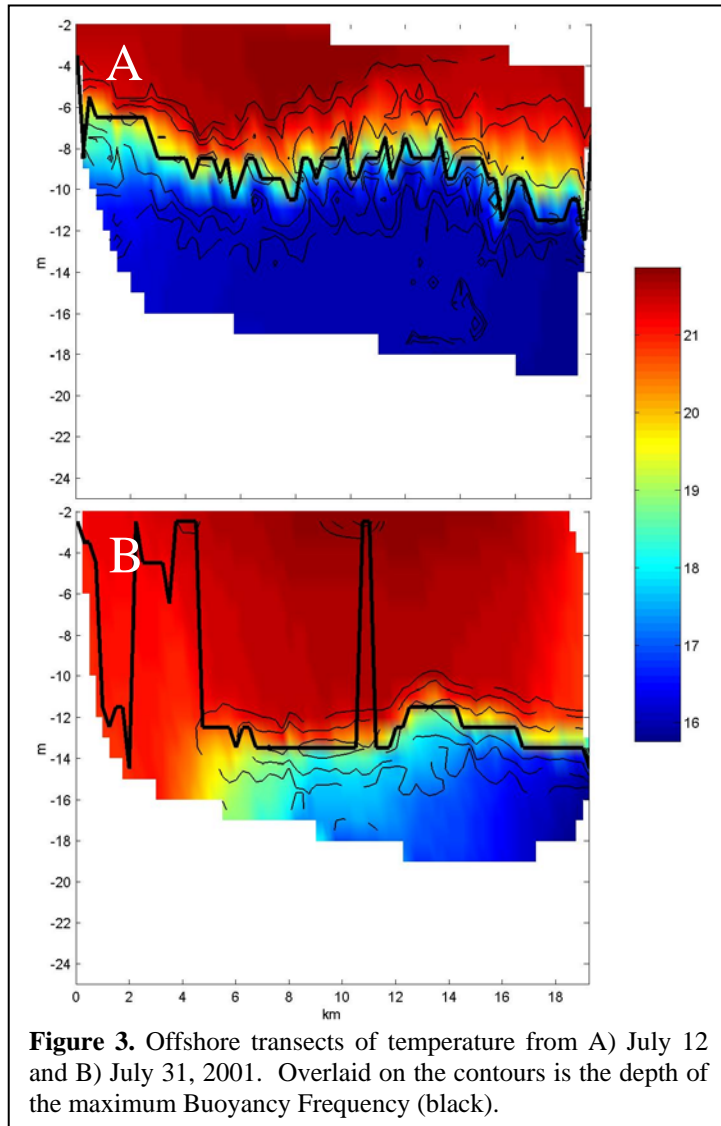
There was weak upwelling associated with southerly wind forcing early in the summer of 2001, as was the case for 2000. However, the coastal region was dominated by winds from the north, which forced surface waters onshore creating a downwelling condition (**Fig. 2A**). While there was a steady increase in phytoplankton biomass over this period, the persistent onshore surface flow advected high chlorophyll water into the study region (**Fig. 2B**). Vertically the peak biomass was associated with the maximal density gradients in the water column, with the highest loads associated with the largest gradients in temperature.

Sampling was conducted 21 of the 28 days in the sampling period. Two ships were used in this effort. The first ship had two towed systems. 1) A Small Water Area Twin Hull (SWATH) vehicle designed by GoldCoast Yachts and constructed by Rutgers was used to tow an RD Instruments Acoustic Doppler Current Profiler (ADCP). 2) Also towed was a Guildline "Minibat" undulating tow-body equipped with a Falmouth Scientific Inc. (FSI) Conductivity Temperature Depth (CTD) sensor, a Wetlabs Fluorometer, and a D&A Instruments Optical Backscatter Sensor (OBS). The "Minibat" uses wings to fly between the surface and the bottom to provide full water column

profiles of temperature, salinity, water clarity and biological fluorescence. The comprehensive optical instrumentation package aboard the second vessel included a Wetlabs AC9 (absorption and attenuation meter at 9 wavelengths) and SaFIre (spectral fluorescence meter), Satlantic OCR (Ocean Color Radiometer) and Hyperspectral TSRB (Tethered Spectral Radiometric Buoy), Hobi Labs Hyperspectral HydroRad 3, Hobi Labs Hydroscat 6, Falmouth Scientific Inc. (FSI) CTD (Conductivity Temperature Depth), and LISST (Laser in-situ Spectral Transmissometer). Along with these instrument measurements, samples were collected for phytoplankton absorption and pigmentation to relate phytoplankton community structure with physical forcing events.
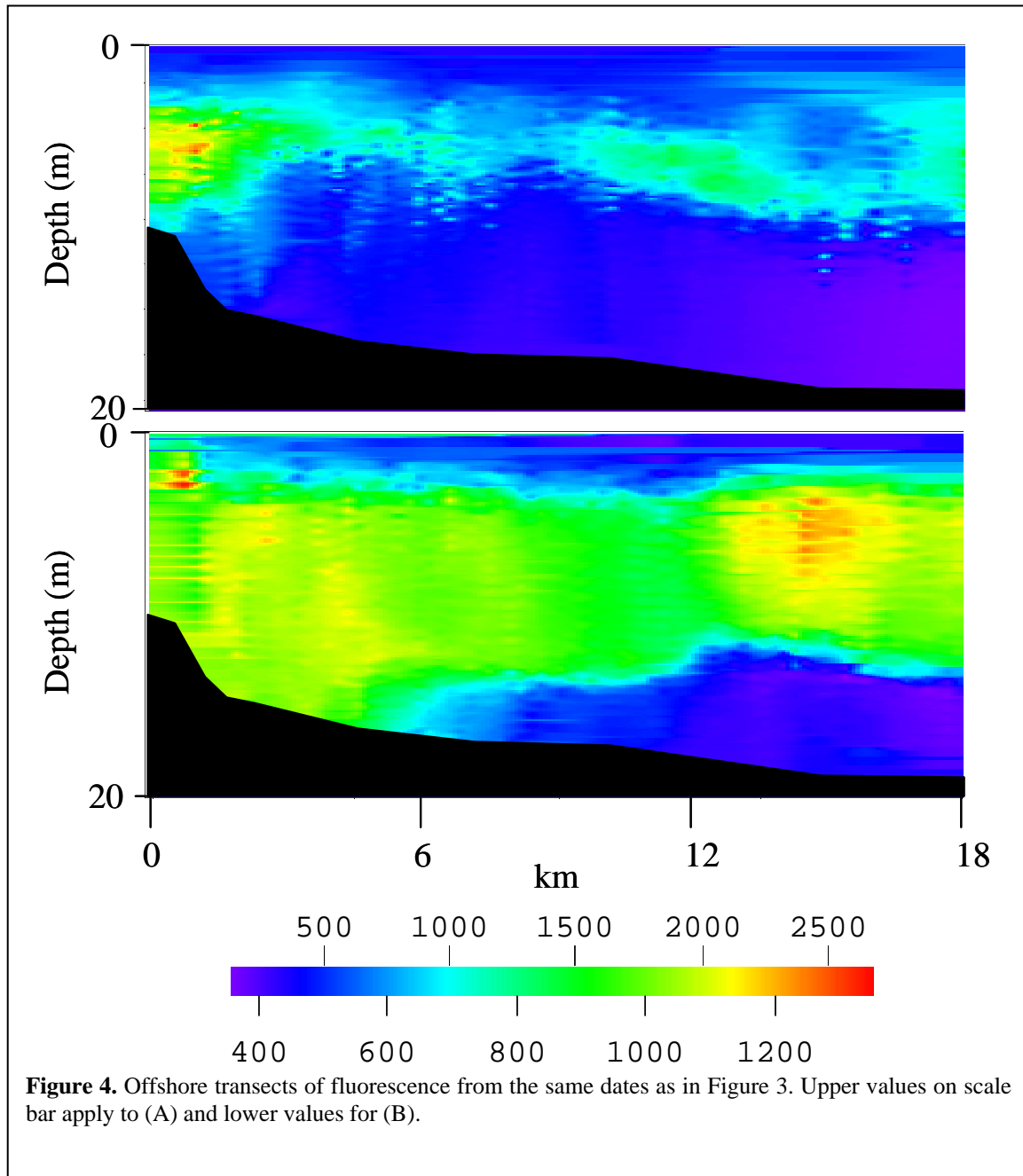
Nine hundred and eighty-seven discrete samples were taken during the summer of 2001; 234 for particulate absorption, 95 for CDOM absorption, 233 for fluorescence, 97 for POC, 78 for oxygen and 250 for HPLC pigmentation. Most of the samples taken were surface samples, as the aim of this season was to validate remote sensing platforms (see below). These samples were transported to Cal Poly State University and analyzed from September 2001 to February 2002. Data from the 2001 season is fully processed and is currently the source for publications and presentations.
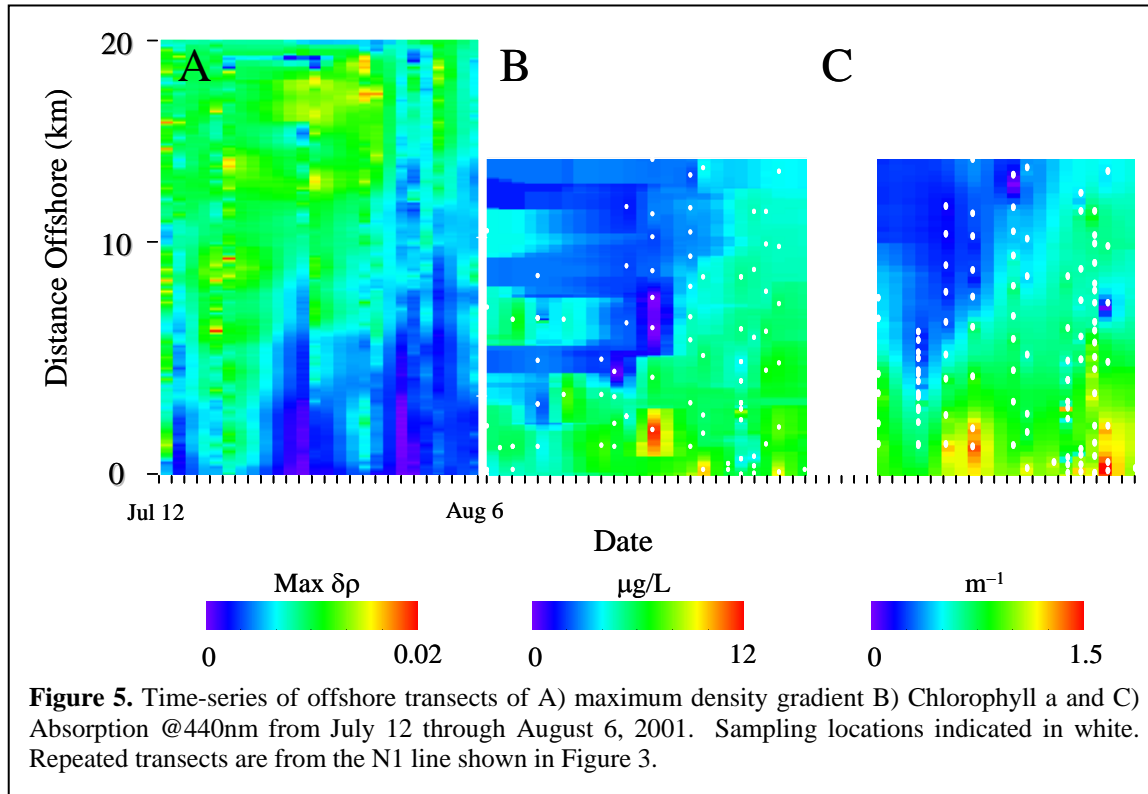

Figure 3. Offshore transects of temperature from A) July 12 and B) July 31, 2001. Overlaid on the contours is the depth of the maximum Buoyancy Frequency (black).

1) Coherance Between Physical Forcing and Biological Dynamics

Data from two offshore profiling nodes during the 2001 experiment showed a high degree of variability in depth and time with respect to temperature and fluorescence (**Fig. 2**). Temperature ranged from 10C°-24C°, with three periods (July 15-19, 26, 30) where there were deep-water intrusions from the shelf as evident by cold, saline water in the lower portions of the water column. Cross-shore transects by the R/V Caleta along the N1 line approximately 5km to the northeast of the profilers showed the cross-shore dynamics of the pycnocline during these periods of cold water intrusion and downwelling (**Fig. 3**). Maximum stratification occurs near the 18-degree isotherm
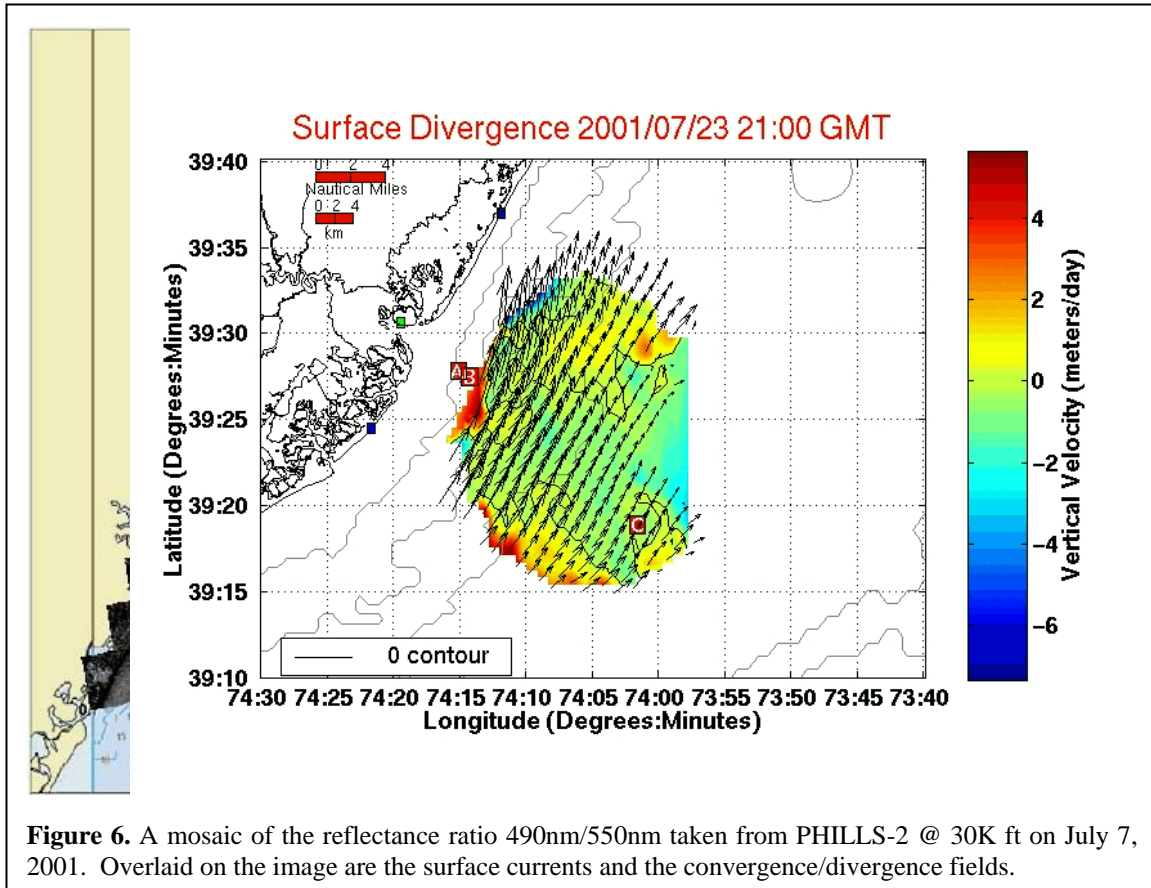
for both conditions. During downwelling conditions however, the vertical gradients were minimal where warmer water extended to the bottom of the water column as far as 8 km offshore. This reduction in stratification inshore results in increased mixing potential and could increase the resuspension of bottom material into the surface waters. Biomass along these same lines illustrate that maximum phytoplankton loads are associated with maximum density gradients within the water column, with varying degrees of surface expression depending on the vertical fluctuation in the physical structure (**Fig. 4**). During downwelling conditions, phytoplankton was more evenly distributed throughout the water column and not concentrated on the density gradient, providing evidence for more vertical exchange during the weakly stratified conditions.

Figure 4. Offshore transects of fluorescence from the same dates as in Figure 3. Upper values on scale bar apply to (A) and lower values for (B).

Figure 5. Time-series of offshore transects of A) maximum density gradient B) Chlorophyll a and C) Absorption @440nm from July 12 through August 6, 2001. Sampling locations indicated in white. Repeated transects are from the N1 line shown in Figure 3.

Looking at the physical stability of the water column on the same transect line over the sampling season, it is evident that the density gradient nearshore became weaker as the season progressed (**Fig. 5**). Maximum vertical density gradients were seen inshore early in the season and remained consistent offshore the entire season. The surface chlorophyll biomass from discrete samples increased as the stratification level decreased (**Fig. 5B**). Chlorophyll biomass integrated to the depth of the maximum density gradient showed identical time/space coherence (data not shown). Perhaps one of the most surprising findings was that not only did the overall phytoplankton biomass increase, but the community structure in phytoplankton appeared to also be influenced by the physical nature of the system. While diatoms dominated the entire area with more than 45% of the chlorophyll, there were time/space changes in some communities that reflected the physical changes. Prymnesiophytes nearshore increased as the stratification decreased during the downwelling. Haptophyte communities showed the opposite trend. For both Cyanobacteria and Dinoflagellates, communities appeared to be influenced by the onshore/offshore advection. These findings shed new light into the timescales and mechanisms for community structure change that traditionally have been examined over seasonal time scales and space scales of 10s-100s of kilometers. This transition to higher surface biomass was also seen in the surface inherent optical properties. Absorption increased from 0.2 nearshore early in the season to values of >1.5 towards the end of the sampling season (**Fig. 5C**). The linkage between in-water physical, biological and optical dynamics was one of the goals of this project. Another goal was to assess the degree to which remote sensing could be applied. Two questions were addressed during the 2001 season and are presently being worked on. One is the coherence between convergence zones and spatial distribution of in-water biological signals (phytoplankton).

During the 2001 season in collaboration with the Florida Environmental Institute (FERI), hyperspectral overflights were made of the LEO-15 area that was concurrently collecting HF radar maps of surface current direction and velocity. A mosaic image of one of these efforts on July 23 is shown in **Figure 6**. For this day, strong northward currents are defining the optical front that exists 5-7 km offshore. In general however, initial data

Figure 6. A mosaic of the reflectance ratio 490nm/550nm taken from PHILLS-2 @ 30K ft on July 7, 2001. Overlaid on the image are the surface currents and the convergence/divergence fields.

suggests that the real-time current maps applied to images flown at the identical time may not best reflect the in-water reflectance data and that a current "history" or lag, which in itself is dependent on the intensity of any given event, is needed to make causal connections to the imagery.

Work just completed on this database through collaboration with a former student working on the project, Matthew Oliver, developed a novel approach to identifying and classifying watermass based on both physical characteristics and optical properties. Sea surface temperature and ocean color satellite imagery were collected during the experiment. We use this imagery as a case study to develop a water mass analysis and classification scheme that objectively describes the locations of water masses and their boundary conditions. This technique uses elements of multivariate cluster analysis in concert with a newly developed genetic expression algorithm to objectively determine the number of water types in the region based on ocean color and sea surface temperature measurements. Then, through boundary analysis of the water types identified, we map the boundaries of the major water types and describe the strengths between them using parameter space distances. These results confirmed by surface currents (**Figure 7**) show that optical fronts are coherent with current boundaries (12-hour averages) and suggest

this approach can be used to track the development of water masses. A paper on this was published.
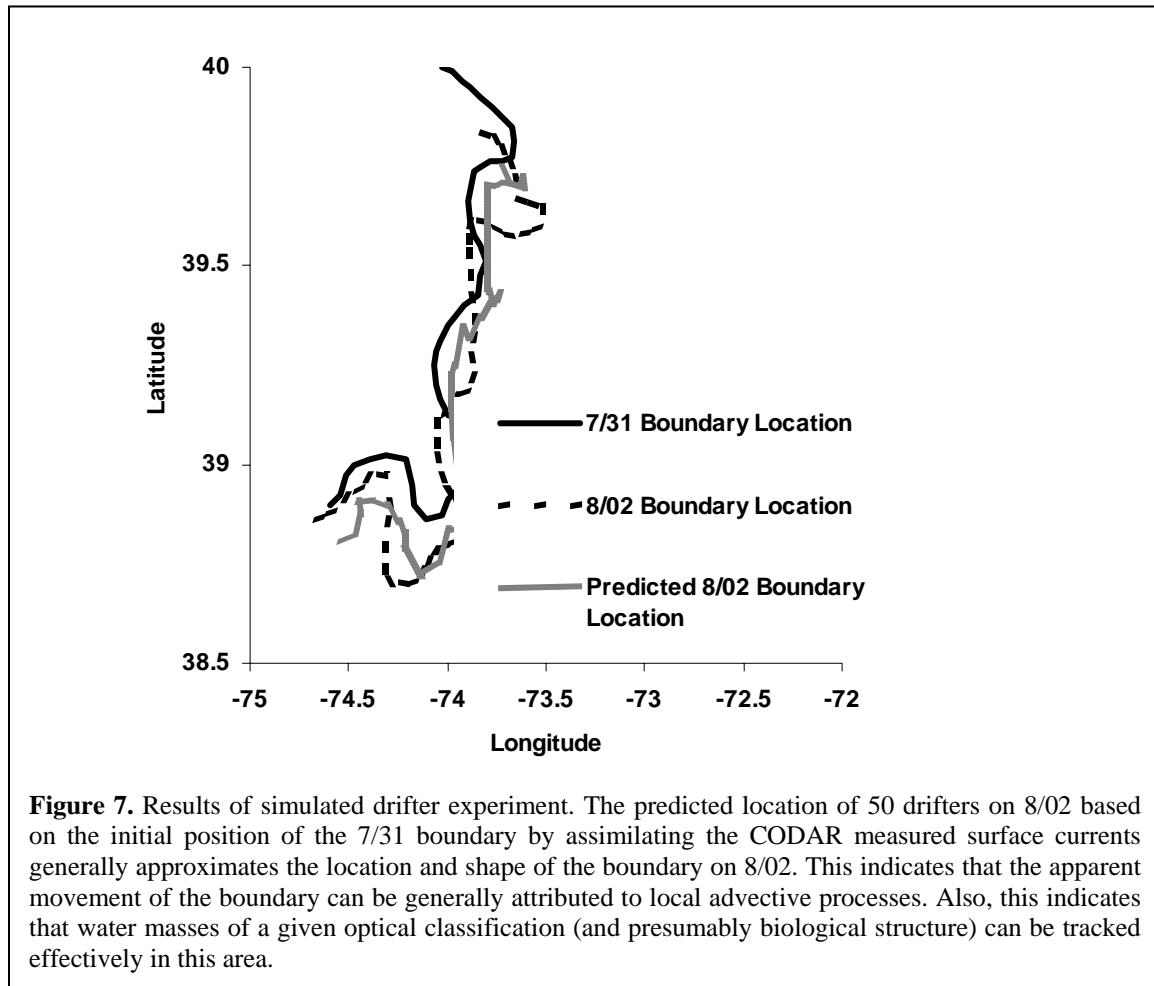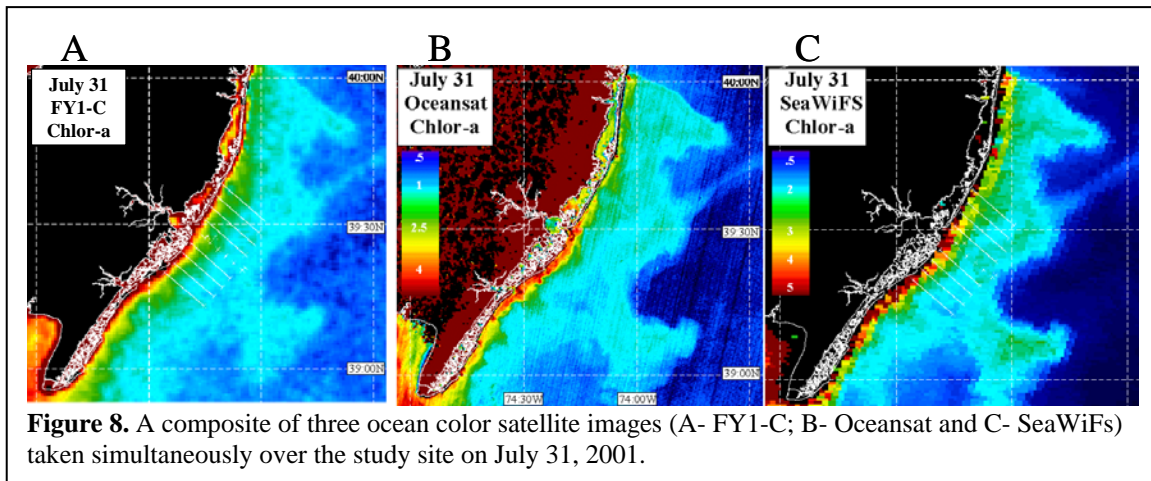

Figure 7. Results of simulated drifter experiment. The predicted location of 50 drifters on 8/02 based on the initial position of the 7/31 boundary by assimilating the CODAR measured surface currents generally approximates the location and shape of the boundary on 8/02. This indicates that the apparent movement of the boundary can be generally attributed to local advective processes. Also, this indicates that water masses of a given optical classification (and presumably biological structure) can be tracked effectively in this area.
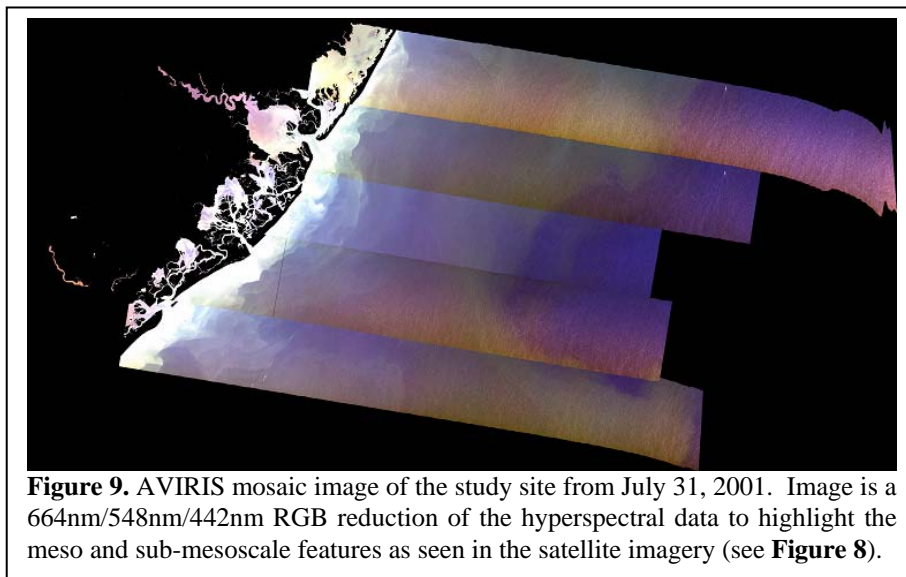
2) Defining Critical Space Scale Dynamics in the Coastal Environment

The other remote sensing focus was attempting to define the critical spatial scales for biology in the coastal environment. Initially it was thought that over sampling features within the pixel size of existing remote sensing platforms (i.e. SeaWiFs) would be adequate to address the question. After two seasons, it was clear that the dynamics within the system are too variable and that synoptic sampling on that scale was not possible. Another approach was undertaken using multiple RS platforms of differing ground resolution to address the same overall goal, understanding that in-water ground validation of the reflectance signals were imperative. In a supplementary grant and in collaboration with the Naval Research Laboratory (DC), we were able to have the area overflown by NASA's ER-2 AVIRIS sensor. This in addition to NRL's PHILLS sensor (aboard an Antinov @ 5k ft), FERI's PHILLS-2 sensor (aboard a NOAA Citation @ 30K ft), and a constellation of ocean color sensors (SeaWiFS [1.1km res.], MODIS, OceanSat [Indian @0.25km res], and FY1-C [Chinese @1km res.]), provided an unprecedented array of platforms to address the goals of this project, with ground spatial resolution

ranging from 1m to 1 km. On July 31, 2001, all of this sensors past over the study area with 6 hours of each other, providing the most comprehensive RS dataset to date. This was also a day with no visible clouds, requiring minimal atmospheric correction and an optimal dataset for sensor comparison. A composite of three of the ocean color satellites clearly indicates the similar nearshore features in the region and the promise for cross comparison of sensors (**Figure 8**). In addition to the RS platforms, there was ground atmospheric correction data taken and three ships within the study site that collected complete transects of the physical, biological and optical data for validation. Work this year has been focused on getting the data from the AVIRIS from data tapes representing multiple passes to a single image format available for comparison. This has not been a trivial exercise given that the AVIRIS sensor is not optimized in the visible wavelengths and the atmospheric correction approach needing to be consistent with those applied to the other imaging datasets (i.e. PHILLS). We completed producing a single mosaic for

Figure 8. A composite of three ocean color satellite images (A- FY1-C; B- Oceansat and C- SeaWiFs) taken simultaneously over the study site on July 31, 2001.

the day of interest which highlights the mesoscale features as seen in figure 7 as well as the sub-mesoscale features (20m resolution) often represented in the data collected *in situ* (**Figure 9**). This dataset has been the focus of work being conducted with NRL DC and FERI and has produced a number of papers.

Figure 9. AVIRIS mosaic image of the study site from July 31, 2001. Image is a 664nm/548nm/442nm RGB reduction of the hyperspectral data to highlight the meso and sub-mesoscale features as seen in the satellite imagery (see **Figure 8**).

3) A New Tool for *in situ* Spatial Validation of Remotely Sensed Products
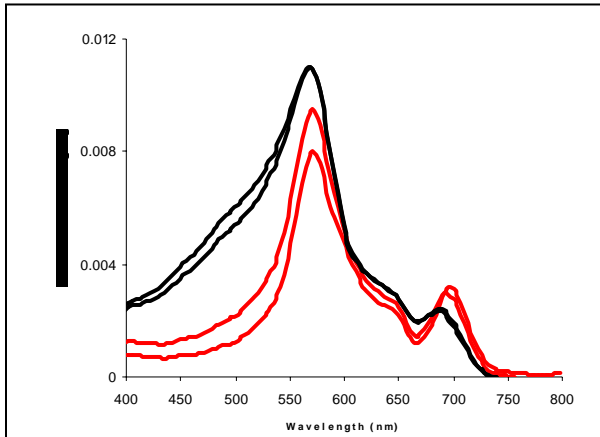

Figure 10. Hyperspectral reflectance measured from tethered radiometric buoy in San Luis Obispo Bay on October 17th, 2002. Data collected within 20 m of each other show two stations in plankton rich diatom-dominated waters (black lines) and two station in a substantial red tide bloom (red lines) with significant spectral depression in the blue and green reflectance wavelengths.

This study has made it possible to examine some of the limitations in validation of remotely sensed products. With new sensor development, such as the PHILLS, the ground resolution has surpassed our ability to sufficiently characterize a given space with point measurements. This has been especially true in coastal regions where significant variability (order of magnitude) can occur within meters. As example of this is seen in surface reflectance data collected along the California coast during October 2002 as part of another PHILLS HS remote sensing effort. Within only 5-10 m, reflectance values were significantly different (**Figure 10**), illustrating a critical need to develop new methods for ground validation that can near synoptically assess the water column optical properties.

As a result of the PECASE award, we developed a new tool to spatially validate remote sensing imagery (aircraft and/or satellite) over relevant scales in coastal waters. We have taken a platform that we have developed through an ONR program and adopted it for measurement of apparent and inherent optical properties (**Figure 11**). The platform is an autonomous underwater vehicle (AUV) that navigates on centimeter accuracy using
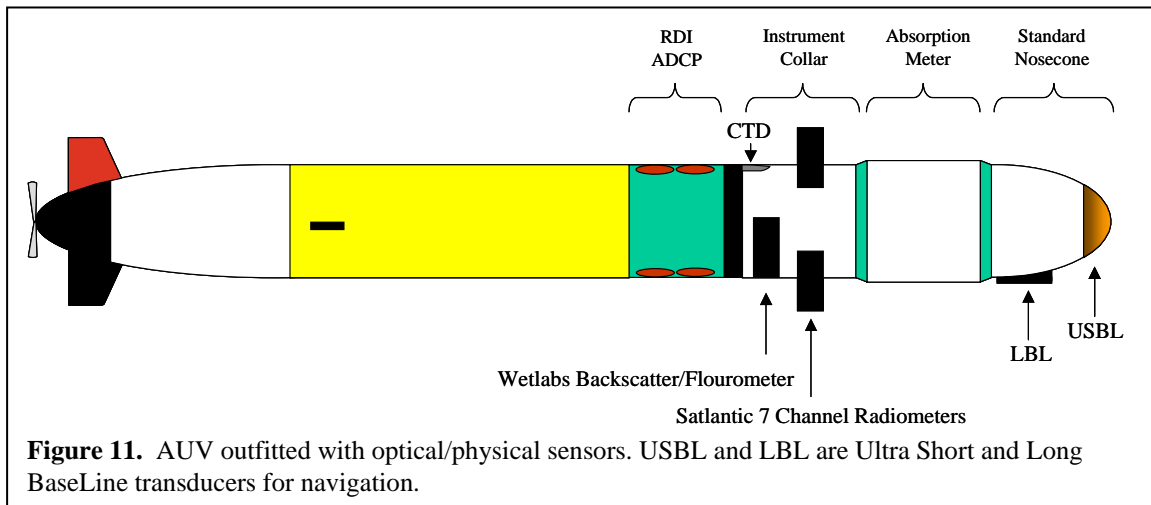

Figure 11. AUV outfitted with optical/physical sensors. USBL and LBL are Ultra Short and Long BaseLine transducers for navigation.

acoustic navigation. The AUV has been used by our laboratory for two years in coastal environments and has flown approximately 1500km without a decrease in functional performance. We outfitted the forward section with multispectral upward looking E_d sensors and downward looking L_u sensors for estimation of remote sensing reflectance at

any depth (the vehicle can be programmed to remain at a fixed depth). The concept was field tested during the summer of 2000 by collaborators at WHOI and Dallhousie University.

The REMUS AUV is a propeller driven platform 160 cm in length and 19 cm in diameter, weighing 37 kg. Because of its relatively small size it is hand deployable by two people. Four Lithium-ion batteries power the vehicle for maximum mission distances at 5 knots of greater than 80 km. The REMUS has four main sections: a nose section, an RD Instruments Acoustic Doppler Current Profiler (ADCP), a mid-body, and tail section. The versatility of the vehicle with regards to size, mission duration (12 hrs @ 5 knots) and adaptive sampling capabilities (level flight, terrain following, grid pattern, yo-yo, loitering and all combinations of these) allow for systematic measurements in the coastal ocean. For this study the REMUS has been modified, through collaboration with Hydroid Inc., to include an additional module between the nosecone and the vehicle's bulkhead at the ADCP (**Figure 12**). This module accommodates the extended Ocean Sensors 200 CTD, a Wetlabs ECO-series backscatter/fluorometer, a Satlantic

Figure 12. REMUS AUV being deployed off Florida with integrated spectral radiometers. Upwelling radiance sensor is directly below the 7-channel irradiance sensor.

downwelling irradiance OCR-507I sensor and a Satlantic upwelling radiance OCR-507R sensor. The wavelengths for the OCR sensors are centered at 412, 442, 490, 532, 555, 669 and 683nm with 10nm bandwidths. Data are collected at 2 Hz with a nominal vehicle speed of 1.7 m/sec, yielding a horizontal data resolution of 0.85 m for the optical measurements. The offset distance between the two cosine surfaces is 21cm. The sensors are positioned alone the midline of the vehicle just aft of the nose section (**Figure 12**). The radiance sensor is flush with the keel of the vehicle, with the irradiance sensor protruding 2cm above the line of the vehicle.
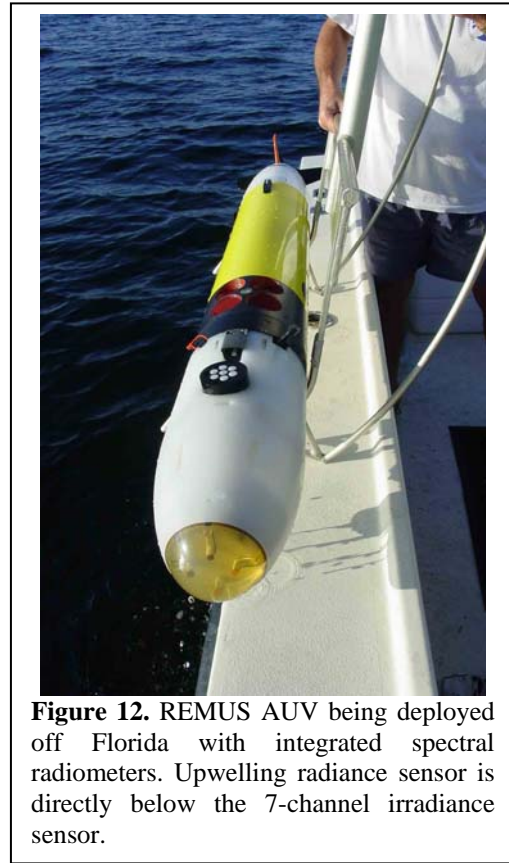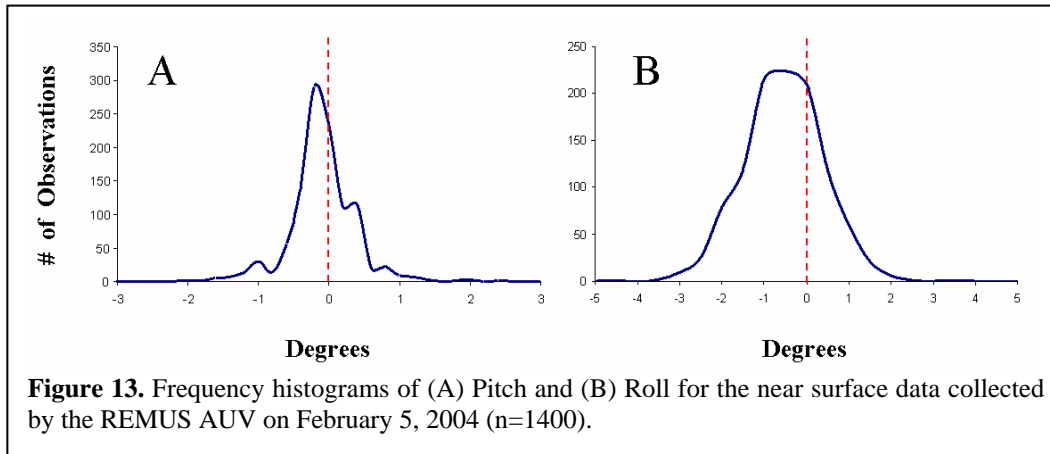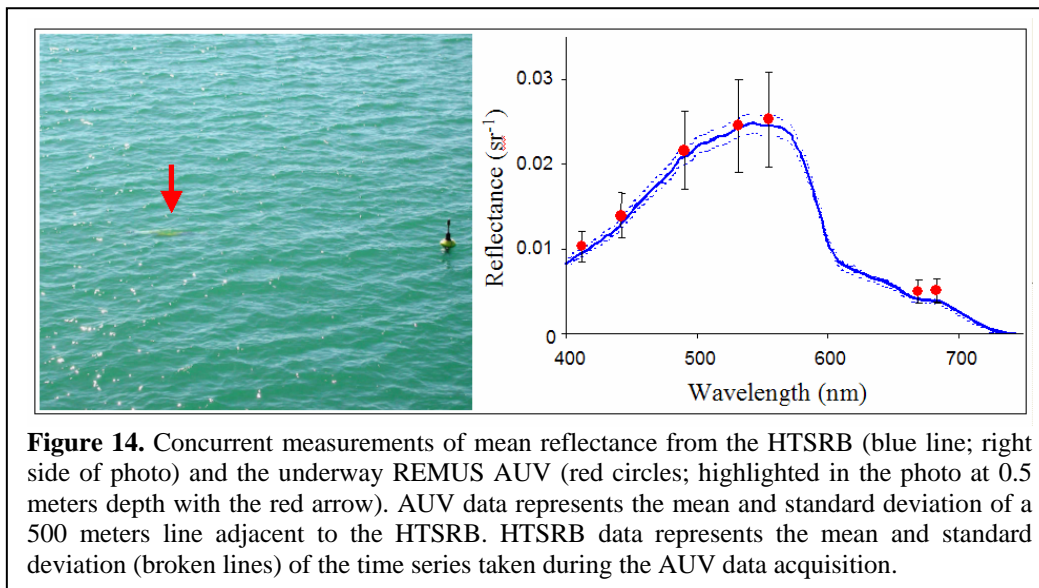
Prior to examining the spectral data from the REMUS, it is important to assess the stability of the platform. The near surface data (0.5m) is used here to quantify the maximum pitch and roll potential. **Figure 13** shows the frequency histograms of the pitch/roll data and illustrate the stability of the AUV. The distribution of data for pitch show symmetrical shoulders that are a result of the pitch up and pitch down responses of the vehicle to maintaining a target depth. The roll data indicate the vehicle is displaced half a degree to starboard due to ballasting, which was corrected in subsequent missions. The data are well within the limit of 10 degrees recommended by the SeaWiFS protocols (Mueller and Fargion 2002) and demonstrate the REMUS AUV as a robust platform for characterizing in water optics.

Figure 13. Frequency histograms of (A) Pitch and (B) Roll for the near surface data collected by the REMUS AUV on February 5, 2004 (n=1400).

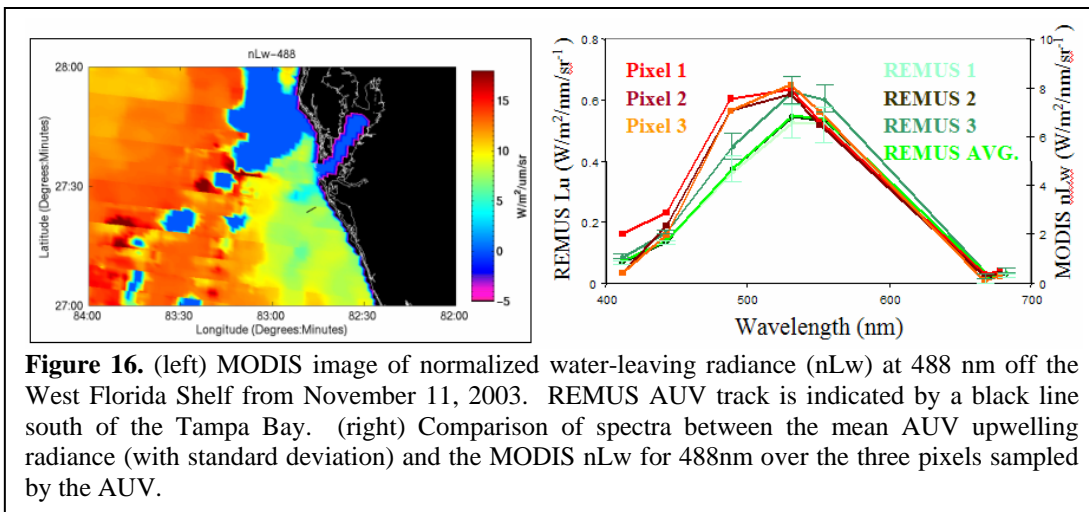The direct comparison between the simultaneous measures of spectral reflectance measurements taken from the REMUS AUV and the HTSRB correlated well both spectrally and in the amplitude of the signal (**Figure 14**). The HTSRB spectrum, especially the blue and red portions, is slightly lower than the reflectance measured by the AUV. This is most likely a result of the above and below surface differences in downwelling irradiance between the two sensors.

Figure 14. Concurrent measurements of mean reflectance from the HTSRB (blue line; right side of photo) and the underway REMUS AUV (red circles; highlighted in the photo at 0.5 meters depth with the red arrow). AUV data represents the mean and standard deviation of a 500 meters line adjacent to the HTSRB. HTSRB data represents the mean and standard deviation (broken lines) of the time series taken during the AUV data acquisition.

The repeated measures of *in situ* reflectance measured by the AUV also show the vehicle's ability to map the vertical differences affecting the spectral attenuation of the light field (**Figure 15**). The vehicle was run across an optical frontal boundary that had been identified in a previous mission. High optical backscatter (**Figure 15B**) and chlorophyll (measured by fluorescence; not shown) on the initial portion of the transect significantly reduced the reflectance ratio (**Figure 15A**). As indicated from these data, the optical front was located approximately 1.5 below the surface and was not directly visible from the surface.
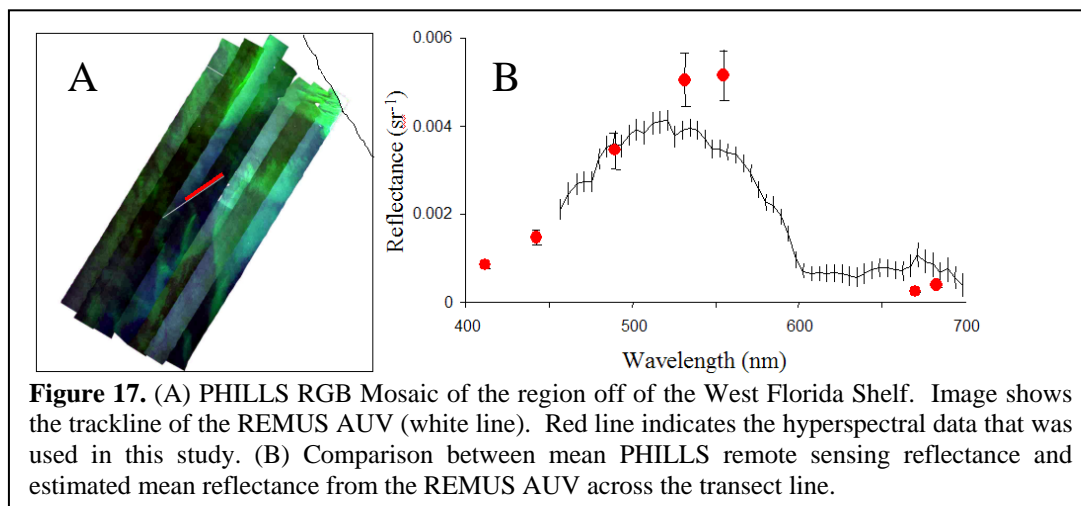
Figure 15. Vertical distribution of (A) remote sensing reflectance taken from the REMUS AUV along a 700 m transect line. The AUV was run horizontally at multiple depths (0.5, 0.75, 1.0, 2.0, 3.0 and 4.0 m). (B) Concurrent measure of the optical backscatter.
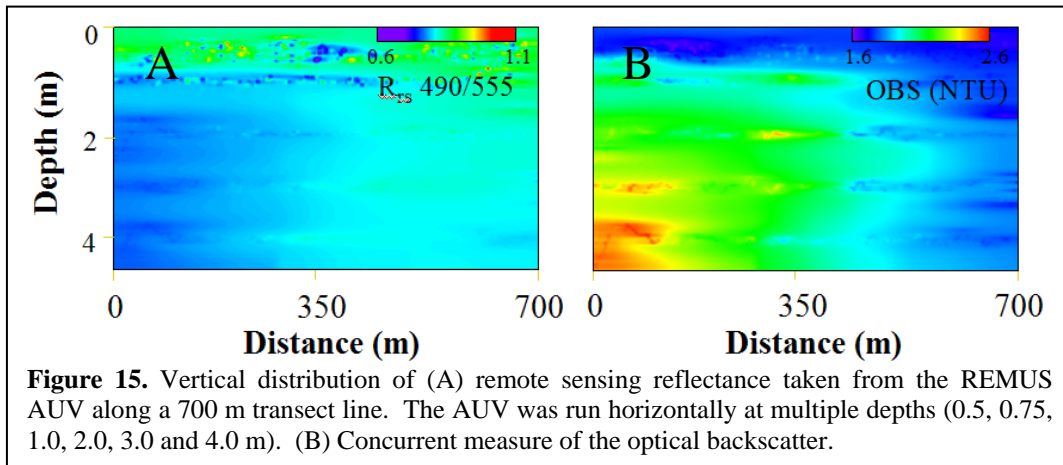
Field Application (Florida) On November 7, 2003, the REMUS AUV was deployed on the West Florida Shelf off Sarasota as part of a nested autonomous sampling grid approach with gliders for the detection of the red tide organism *K. brevis*. The AUV was run along a 4 km East to West transect (onshore to offshore). The depth ranged from 10 to 13m over the transect. In this test mission, the vehicle was operated in depth mode at 3m to avoid the frequent north-south small boat traffic. Concurrent with the AUV deployment at 18:00 (UTC) for comparison were a synchronized overflight of the PHILLS hyperspectral sensor and a MODIS ocean color pass ~4 hours earlier at 13:45 (UTC).

Figure 16. (left) MODIS image of normalized water-leaving radiance (nLw) at 488 nm off the West Florida Shelf from November 11, 2003. REMUS AUV track is indicated by a black line south of the Tampa Bay. (right) Comparison of spectra between the mean AUV upwelling radiance (with standard deviation) and the MODIS nLw for 488nm over the three pixels sampled by the AUV.

Although the REMUS AUV transect only covered a 4km line, it was sufficient for comparison over three MODIS pixels (**Figure 16**). The spectral data from the AUV were delineated based on the pixel boundaries and averaged for comparison. The spectral characteristics of MODIS derived nLw and the REMUS Lu show good qualitative agreement. The quantities of nLw and Lu are not directly comparable, however, due to the surface, and differences are due to light transmission into and out of the surface (indicated by the spectral shift in the maximum Lu to the green) as well as the local atmospheric effects that influence the retrieval algorithms. There was also streaking in

the image from that day, which may also have influenced the retrieval products. Despite this, the spectral shapes of the spectra are similar. More work is presently being done to address the water interface and derive estimates of Lw for the REMUS AUV for a direct comparison.
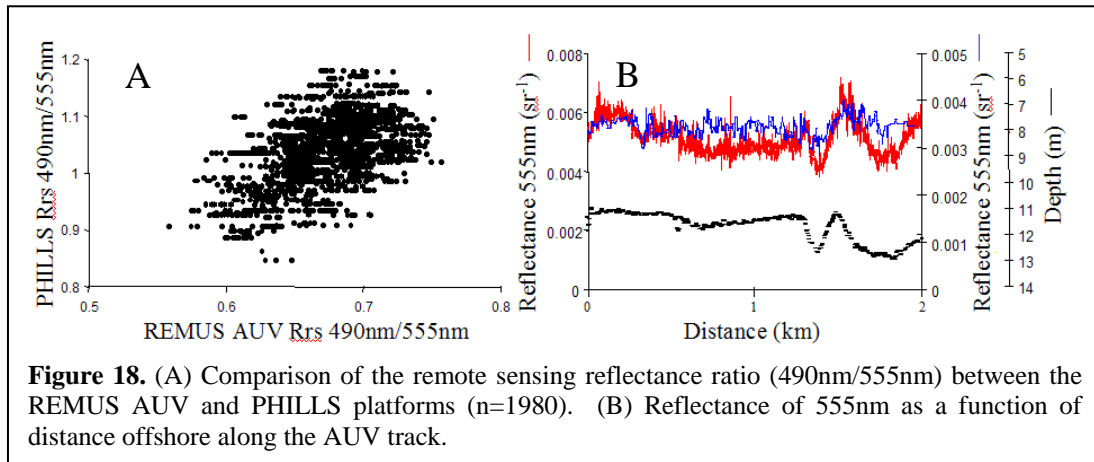
On the same day, multiple flight lines were flown over the area by the PHILLS sensor. Atmospheric conditions over the transect were heterogeneous making correction across the entire scene difficult. As an initial test, the portion of the overflight over the transect line that contained minimal influence from the atmosphere was used to compare to the *in situ* AUV radiometric measurements (**Figure 17A**). Mean spectral remote sensing reflectance from the PHILLS and the REMUS AUV (estimated by the ratio of upwelling radiance to downwelling irradiance) were compared across the transect. There was good quantitative agreement, however, there was a larger signal in the green wavelengths for the AUV (**Figure 17B**).

Figure 17. (A) PHILLS RGB Mosaic of the region off of the West Florida Shelf. Image shows the trackline of the REMUS AUV (white line). Red line indicates the hyperspectral data that was used in this study. (B) Comparison between mean PHILLS remote sensing reflectance and estimated mean reflectance from the REMUS AUV across the transect line.

Further examination of the data along the transect, showed significant linear agreement between the two platforms for the reflectance ratio (490nm to 555nm; **Figure 18A**). The differences in scale are again resulting from the depth of the AUV and transmission across the air-surface interface. Reflectance at 555nm from both platforms along the transect line showed similar patterns of inflection (**Figure 18B**). One of the great advantages that the REMUS AUV affords is its ability to simultaneously acquire optical data as well as bathymetry to quantify the impact of bottom reflectance on remote sensing reflectance. **Figure 18B** shows the impact of bottom, near km 1.5 of the transect, with the inflections in reflectance from both the AUV and the PHILLS corresponding to bathymetry. In contrary, there are changes in the signal that do not necessarily correspond in changes in bottom depth, for example at km ~0.3. These inflections in both sensors were a result of differences in the water column optical properties or in the color of the bottom due to nephloid layers, substrate differences or vegetation cover.

While these initial efforts used constant depth missions for comparison to in situ instrumentation and airborne and satellite platforms, future efforts will focus on the ability of the vehicle to quantify vertical differences in water column properties by using a combination of level flight, saw-tooth patterns and step patterns. Quantifying the small depth differences in apparent optical properties throughout the water column, with

attention to the near surface, will lead to direct estimates of nLw and Rrs for comparison with above-water data.

Figure 18. (A) Comparison of the remote sensing reflectance ratio (490nm/555nm) between the REMUS AUV and PHILLS platforms (n=1980). (B) Reflectance of 555nm as a function of distance offshore along the AUV track.

These deployments show promise for AUV platforms to play a role in validation of remote sensing products in the coastal ocean. They also demonstrated the AUV's ability to simultaneously measure bathymetry to assess the influence of bottom reflectance. The REMUS AUV is also a tool in its own right for measurements of in-water constituents on scales relevant to coastal processes.

Data Products (July 15, 2000 – July 14, 2005)

In addition to the publications relevant to this grant below, there is a special volume being worked on directly related to this NASA funding. The volume will be focused one on the spatial scale of biological features using remote sensing data from 7 different platforms (and spatial resolution; see above) on July 31, 2001. The target journal for this effort will be *Remote Sensing of the Environment* with Curtis Davis (NRL DC), Paul Bissett (FERI) and Mark Moline (Cal Poly) spearheading the effort. In addition to this volume, work generated from this grant will be contributing to a number of submissions in a special volume of *Oceanography* focused on marine optics due by the end of 2003.

Presentations

The Oceanography Society/UNESCO – Paris, France in June 2005.

APPLICATIONS OF AUTONOMOUS VEHICLES IN THE COASTAL OCEAN

Moline, Mark A.[1]; Blackwell, Shelley M.[1]; Robbins, Ian[1]; Kirkpatrick, Gary[2]; Schofield, Oscar M. E.[3]

Ocean Optics XV, Freemantle, Australia in November, 2004.

Moline, M. A., S. Blackwell, W. P. Bissett, G. Kirkpatrick, D. D. R. Kohler, M. Sauer and O.M. Schofield. An autonomous platform for spatial ocean color validation.

The Oceanography Society /ASLO, Honolulu HI in February, 2004.

Moline, M. A., S. Blackwell, <u>W. P.</u> Bissett, J. Case, G. Kirkpatrick and O.M. Schofield. Autonomous sampling of coastal ocean environments.

The Oceanography Society - Oceanology International Americas Ocean Conference. New Orleans in June 2003.

Moline, M. A., S. Blackwell, W. P. Bissett, S. Glenn, M. Purcell, C. von Alt and O. Schofield. AUV flight path optimization for sampling biological fields in the coastal ocean.

Ocean Sciences (AGU/ASLO), Salt Lake City in February, 2003.

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Educational Activity

One of the primary goals of this project was to provide undergraduate and graduate students with research experience in cross-disciplinary multiplatform approaches to learning earth system science.

During the 2000 season, 4 undergraduates were supported by this project and participated in sample collection and analyses (Taylor Newton, Dwight Peterson, Jessica Pearson, Erika Peters). Three of these students used these data as the subject for their senior thesis project (Ryan Knoth, Erika Peters, Dwight Peterson). Four students also coauthored presentations at a national meeting. This project also funded three graduate students (Cristina Orrico, Shelley Blackwell and Matthew Oliver) for that year to analyze related samples and data.

During the 2001 season, 2 undergraduates were supported by this project and participated in sample collection and analyses (Jessica Pearson and Nova Perrill). Both of these students used these data as the subject for their senior thesis project. Jessica Pearson also coauthored presentations at a national meeting (winning best undergraduate poster). On campus, this grant has supported and provided data for 6 other undergraduates. This project also funded four graduate students (Cristina Orrico, Shelley Blackwell, Erika Heine and Matthew Oliver) for that year to collect and analyze related samples and data.

During the 2002 season, 2 undergraduates were supported by this project and participated in sample collection and analyses (Jessica Pearson and Dorinda Shoemaker). This project also funded four graduate students (Cristina Orrico, Shelley Blackwell, Erika Heine and Matthew Oliver) for that year to collect and analyze related samples and data.

During the 2003 season, 1 undergraduate was supported by this project and participated in data analyses (Charles Villefane). This project also funded four graduate students (Cristina Orrico, Shelley Blackwell, Ian Robbins and Michael Sauer) for that year to collect and analyze related samples and data.

During the 2004 season, 2 undergraduates were supported by this project and participated in data analyses (Robyn Matteson and Jeff Sevadjian). This project also funded two graduate students (Ian Robbins and Michael Sauer) for that year to analyze data.

The six graduate students supported by this project have completed their Masters thesis and have contributed to data products. The graduates are presently in the following locations/capacities since graduating; Ian Robins recently graduated, Michael Sauer is a Ph D student at the University of Maine, Cristina Orrico is a PhD student at Oregon State University, Shelley Blackwell is a technician in M. Moline's laboratory, Erika Heine is a PhD student at Johns Hopkins and Matthew Oliver is a PhD student at Rutgers University.

Related Projects
The following are related recently funded projects that help to provide equipment and infrastructure to achieving the goals and objectives of this NASA project.

ONR – "Hyperspectral remote sensing of the coastal ocean: adaptive sampling and forecasting of nearshore in situ optical properties". 1999-2002 (M. Moline).

ONR – "High resolution temporal sampling of the nearshore vertical structure of bioluminescence." 1999-2001 (M. Moline and J. Case).

ONR – "High-resolution structure of bioluminescence potential in the nearshore coastal waters: Processes and prediction." 2000-2003 (M. Moline).