DEVELOPMENT OF NESTED, AUTONOMOUS PHYTOPLANKTON MONITORING TECHNOLOGY

Final Report for Period:
April 2002 – December 2004

MOTE MARINE LABORATORY

SUBMITTED TO:
National Science Foundation

SUBMITTED BY:
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Principal Investigator: Kirkpatrick, Gary J.
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Organization: Mote Marine Lab
Title:
Development of Nested, Autonomous Phytoplankton Monitoring Technology

Project Participants

Senior Personnel

Name: Kirkpatrick, Gary
Worked for more than 160 Hours: Yes
Contribution to Project:

Name: Jones, Clayton
Worked for more than 160 Hours: No
Contribution to Project:
Project engineer for Slocum Gliders at Webb Research Corporation. Participation in this project supported by subcontract from Mote Marine Laboratory.

Post-doc

Graduate Student

Name: Oliver, Matt
Worked for more than 160 Hours: No
Contribution to Project:
Rutgers University graduate student working on phytoplankton species discrimination.

Name: Kahl, Alex
Worked for more tban 160 Hours: No
Contribution to Project:
Rutgers University graduate student working on the adaptive control of AUVs using remote sensing input.

Name: Robbins, Ian
Worked for more than 160 Hours: No
Contribution to Project:

Undergraduate Student

Name: Vasilantone, Devyn
Worked for more than 160 Hours: No
Contribution to Project:
Rutgers University undergraduate student.

Name: Trey, Augie
Worked for more than 160 Hours: No
Contribution to Project:
Rutgers University undergraduate student.

Technician, Programmer

Name: Blackwell, Shelley
Worked for more than 160 Hours: No

Contribution to Project:

Technician at California Polytechnic State University working with REMUS autonomous underwater vehicle.

Name: Kerfoot, John

Worked for more than 160 Hours: No

Contribution to Project:

Technician at Rutgers University conducting Slocum Glider operations.

Name: Hillier, James

Worked for more than 160 Hours: Yes

Contribution to Project:

Technician at Mote Marine Laboratory integrating the optical phytoplankton discriminator in the autonomous underwater vehicles

Name: Lelievre, Scott

Worked for more than 160 Hours: No

Contribution to Project:

Webb Research Corp. mechanical design engineer. Participation in this project support by subcontract to Webb Research Corp. from Mote Marine Laboratory.

Name: Creed, Elizabeth

Worked for more than 160 Hours: No

Contribution to Project:

Other Participant

Name: Schofield, Oscar

Worked for more than 160 Hours: No

Contribution to Project:

Co-PI at Rutgers University. Participation in this project supported by subcontract from Mote Marine Laboratory.

Name: Glenn, Scott

Worked for more than 160 Hours: No

Contribution to Project:

Co-PI at Rutgers University. Participation in this project supported by subcontract from Mote Marine Laboratory.

Name: Moline, Mark

Worked for more than 160 Hours: No

Contribution to Project:

Co-PI at California Polytechnic State University. Participation in this project supported by subcontract from Mote Marine Laboratory.

Research Experience for Undergraduates

Name: Hansen, Allison

Worked for more than 160 Hours: No

Contribution to Project:

Years of schooling completed: Junior

Home Institution: Other than Research Site

Home Institution if Other: Northland College

Home Institution Highest Degree Granted(in fields supported by NSF): Bachelor's Degree

Fiscal year(s) REU Participant supported: 2004

REU Funding: No Info

Organizational Partners

Webb Research Corporation

Webb Research Corporation is a partner in this project supported by subcontract. Webb manufactures the Slocum Glider autonomous underwater vehicle being used as a platform for the optical phytoplankton discriminator (OPD). They train the project staff on glider operations, provide software and structural components for the OPD payload, and collaborate on the technical aspects of the application.

California Polytechnic State University Foundation

The Department of Biological Sciences of the California Polytechnic State Universty is a partner in this project supported by subcontract. Dr. Mark Moline is a co-PI and is providing a REMUS autonomous underwater vehicle as a platform for the optical phytoplankton discriminator.

Rutgers University New Brunswick

The Institute of Marine and Coastal Sciences at Rutgers University is a partner in this project supported by subcontract. Dr. Oscar Schofield is a co-PI and is providing the Slocum Glider autonomous underwater vehicle used as a platform for the optical phytoplankton discriminator.

Other Collaborators or Contacts

1. Hydroid Inc., Flamouth, MA - upgrading the REMUS vehicle (additional battery, conversion of acoustic system to digital for increased range, additional transponders and general maintainence).
2. Chris von Alt, Woods Hole Oceanographic Institute - upgrading the REMUS vehicle software.
3. Eric Terrill, Scripps Institute of Oceanography (MPL) - work with ADCP data to retrieve biological acoustic returns (zooplankton distributions).
4. Andrew Schaffner, Cal Poly statistics department - optimizing AUV flight paths for defining critical length scales (vertical/horizontal) of biological features.
5. Robert Euwema, Mote Marine Laboratory - software development for optical phytoplankton discriminator.
6. Steven Lohrenz, University of Southern Mississippi - Analyses of hyperspectral discrimination techniques.

Activities and Findings

Research and Education Activities: (See PDF version submitted by PI at the end of the report)

The objective of the project was to expand the present use of autonomous underwater vehicles (AUVs) to include the study of in situ distributions of phytoplankton communities. Specifically, this work developed and integrated optically-based phytoplankton discrimination (OPD) instruments into two classes of (AUVs) to provide an end-to-end in situ phytoplankton detection and mapping capability.

Initially the major effort was the miniaturization of the prototype OPD and its integration as an AUV payload (Figure 1). This entailed major mechanical, electronic and software modifications.

A Slocum Glider trial operation was conducted January 12 - 17, 2003 in the eastern Gulf of Mexico. Two Slocum Gliders (minus the OPD) were transported from Rutgers University to Mote Marine Laboratory. The gliders were loaded on the Mote research vessel Eugenie Clark and taken out into coastal waters for deployment. It is noteable that many of the launches and recoveries conducted on the R/V Eugenie Clark were handled by an all-woman glider crew (Figure 2). Two days at sea were dedicated to system checkout and preliminary mission profiles (Figure 3). The third and fourth days at sea were actual autonomous missions flown in tandem by the gliders. On the fourth day the control of one glider was transfered to the Rutgers Coastal Ocean Observation Laboratory in New Jersey. All aspects of those trials were successful.

Following the successful integration of the OPD into a Webb Research Corporation electric glider the design was adapted to the Hydroid REMUS (Figure 5). This completed the first milestone of the project, resulting in two OPD-equipped AUVs (Figure 6) for field tests. The first combined field operation occurred in November 2003 (Figure 8). During these tests a ship discovered a small patch of the red tide organism Karenia brevis several kilometers south of Tampa Bay, Florida. One of the Webb gliders that was already on a mission (red track in Figure 8) was diverted to the site while missions were planned for two other gliders and the REMUS. One of the gliders was equipped with an OPD while the others carried various other bio-optics sensors. The OPD-equipped REMUS experienced power problems requiring the removal of the OPF payload for this mission. The OPD-equipped glider conducted a successful test report low levels of K. brevis. On January 15, 2004

the OPD-equipped glider was launched from a survey vessel in a region suspected to be a bloom of K. brevis (Figure 10). The glider conducted a 30 hour mission while the survey vessel continued its standard route. During its return trip the survey vessel recovered the glider. Microscope cell counts confirmed the findings of the OPD. During the summer, 2004 Ms Allison Hansen was an REU student intern in the Phytoplankton Ecology at Mote Marine Laboratory. Her project included an assessment of the OPD's ability to discriminate algal classes in mixed species communities. She prepared known mixes of four laboratory cultures and processed those through an OPD. In September and October 2004 the glider conducted a cross-shelf survey consisting of six transits between the 10 and 30 meter isobaths (approximately 40 km). This mission ran eleven days until weather conditions began to degrade and recovery was necessary.
The REMUS was deployed again in January 2005 in reponse to another bloom of Karenia brevis. Numerous mission profiles were swum during five one-day missions in the Gulf of Mexico off the coast from Sarasota, Florida.

Gary Kirkpatrick, Oscar Schofield, Mark Moline and Clayton Jones presented talks concerning this project on numerous occasions. On April 17, 2002 at the public lecture series 'Monday Night at Mote' they presented 'From Microscopes to Satellites: The Hunt for Red Tide' detailing the development of phytoplankton detection technologies. At the ASLO summer meeting on June 13, 2002, in the special session on 'Applications of Automated Technology to Detect Environmental Change' they presented, 'In Situ, Autonomous Optical Detection and 3-D Mapping of Harmful Algal Blooms.' Gary Kirkpatrick participated for the project investigators as an invited workshop presenter on optically-based phytoplankton discrimination at the NSF sponsored 'Modern Methods Workshop' at the Botany 2002 Conference on August 4, 2002. On October 22, 2002 they presented 'In Situ, Autonomous Optical Detection and 3-D Mapping of Harmful Algal Blooms' at the Tenth International Conference on Harmful Algal Blooms. Presentations were made at the HABWatch workshop in June 2003 titled 'An Evaluation of Hyperspectral Detection and Monitoring of Bloom Events of the Harmful Alga, Karenia brevis' by Steven Lohrenz et al. and 'Dawn in the New Millennium for Biological Oceanographers' by Oscar Schofield and Scott Glenn. Gary Kirkpatrick presented 'Mapping Karenia Brevis Blooms Utilizing Automated Optical Discrimination' at the 2nd National HAB Symposium December 8-13, 2003. During the Ocean Research Interactive Observatory Networks (ORION) workshop January 4-8, 2004 the PIs presented 'Detecting Harmful Algae Using Autonomous Underwater Vehicles' and 'AUV/New Sensor Deployments off the Coast of California Examining Physical Forcing on Ecosystem Dynamics'. Presentations by the PIs at the 2004 Ocean Research Conference included: 'Utilizing Automated, absorbance-based optical discrimination to Map Phytoplankton Distribution'; 'Near-synoptic Autonomous Spatial Sampling of Coastal Multi/hyperspectral apparent/inherent optical properties'; 'Mapping Red Tide Using Autonomous Underwater Webb Gliders'.

Findings: (See PDF version submitted by PI at the end of the report)

The data collected during initial glider trials in the eastern Gulf of Mexico (Figure 4) showed a weak small-scale physical feature (a density front) that separated two similar water masses. Frontal features and their associated water masses were areas where phytoplankton populations could accumulate and locations where different phytoplankton communities interacted. The optical backscatter data in Figure 4 shows a clear demarcation in the particle backscatter characteristics between the two water masses. This suggests that the two water masses may have contained distinct phytoplankton populations. The optically-based phytoplankton discrimination (OPD) instrument, though not installed for the mission in Figure 4 provides a means of assessing the taxonomic differences and whether there is interaction at the boundary.

The first open water deployment of the OPD-equipped glider off the coast of New Jersey yielded a small, but encouraging dataset (Figure 7). The AUV/OPD instrument was first tested in an estuarine boat basin. The OPD results from that short mission were strongly dissimilar to the target species, Karenia brevis. When deployed offshore the similarity was more like K. brevis, but not high enough to indicate the presence of that species (K. brevis does not occur as far north as New Jersey).

The more extensive field deployment that was conducted in November 2003 yielded an extensive dataset from the three gliders and the REMUS (Figure 9). That was a truly nested scale study with the three gliders covering two ranges of the larger scale and the REMUS conducting a very fine-scale survey within the bounds of the glider missions. A short circuit in the power supply to the OPD on the REMUS eliminated any measurements by the OPD, but the optics and current sensors obtained complete data records over the mission track. The OPD on the glider did detect low levels of Karenia brevis well below the surface of the water. The K. brevis population was strongly advected by the tidal flows along the shelf. On the flodding tide the sensors found water signatures characteristic of oceanic water, whereas on the ebb tide estuarine water moved into the study site from Tampa Bay.

The OPD-equipped glider reported high fractions of Karenia brevis biomass in a bloom patch examined in January 2004 (Figure 11). High cell counts were reported from microscope examination of water samples concurrently collected on the survey vessel that launched and recovered the glider. In Figure 11 the similarity index has been transformed to biomass fraction representing the fraction of the total chlorophyll bimoss contributed by K. brevis. A lower-density layer of water near the surface, emanating from the Tampa Bay area (based on satellite imagery), appeared to contain the highest fraction of K. brevis.

Results from studies conducted by an REU intern demonstrated the ability of the OPD to estimate the amount of chlorophyll in mixed species communities contributed by a particular species (Figure 12). Ms. Hansen prepared several mixes of laboratory cultures and characterized the chlorophyll contribution by each species in the mix. She then processed those mixes through the OPD and using a newly developed algorithm estimated the chlorophyll concentration attributable to each species.

Highly resolved water structure was determined over an eleven day deployment of an OPD-equipped glider over the continental shelf off Sarasota, Florida in September 2004. Along with temperature and salinity the instrument returned, in near-real time, the Karenia brevis sinilarity indices (Figure 13). No K. brevis was detected, but shifts in the phytoplankton community were evident and appeared to be linked to physical changes in the water structure. During the second transit across the shelf the temperature sensor detected a plume of cooler water extending from the bottom to near the surface(Figure 14). This feature was not detected during the first transit. The phytoplankton community (detected by the OPD) in this plume of cooler water was fairly homogeneous and had a character more like that found near the botton on the first transit. This cobination suggests the possiblity of an upwelling of bottom water that suspended the near-bottom phytoplankton community further up in the water column.

A graduate student at California Polytechnic State University is now conducting his research project on the use of the OPD-equipped REMUS to discriminate harmful algal bloom species from non-harmful phytoplankton bloom events. He has conducted several deployments in Florida as well as California, but is still awaiting a HAB event in California to finish his work. Figure 15 illustrates recent results from one of his deployments in a bloom of Karenia brevis off the coast of Florida. It is quite common for that species of dinoflagellate to for dense patches close to the water surface. The REMUS verified that distribution and provided very detailed hydrographic data in the area of the bloom. It is one of our hopes that with these instrumented vehicle we will be able to determine the role of physics in the formation of dense bloom patches.

Training and Development:

Four project personnel, two from Rutgers University and two from Mote Marine Laboratory have received training on technical aspects of Slocum Glider operations. Eight personnel have received hands on experience in the launch and recovery of Slocum Gliders. Two project personnel and a graduate student from California Polytechnic State University have received training on technical aspects of REMUS operations. Five personnel, two from Rutgers University, two from Califorina Polytechnic State University and an REU student from Northland College have been trained on the operation and maintenance of the Optical Phytoplankton Discriminator.

Outreach Activities:

Gary Kirkpatrick, Oscar Schofield, Mark Moline and Clayton Jones presented three talks concerning this project to public groups. On April 17, 2002 at the public lecture series 'Monday Night at Mote' they presented 'From Microscopes to Satellites: The Hunt for Red Tide' detailing the development of phytoplankton detection technologies. On November 7, 2002 they presented 'In Situ, Autonomous Optical Detection and 3-D Mapping of Harmful Algal Blooms' to the Scientists and Engineers Expanding Knowledge (SEEK), a group of scientists and engineers on the Gulf Coast attempting to more widely disseminate information on technical issues. On December 9, 2002 they presented 'In Situ, Autonomous Optical Detection and 3-D Mapping of Harmful Algal Blooms' to the Mote Marine Laboratory volunteer organization. This group is made up of volunteers who interact with the public on a daily basis to inform them of the work being done at Mote. On February 12, 2003 a presentation titled 'Automated Red Tide Surveilance' was made to the Bird Key Yacht Club in an effort to further disseminate notice that AUVs would be operating in local waters.

It is important to this project to keep the community informed about the science that is being conducted in their area. Particularly since this is publicly funded and especially because citizens are very concerned about unusual activities. We acknowledge that the autonomous underwater vehicles could be alarming to uninformed citizens who observe them in the Gulf of Mexico. Therefore we have placed a significant effort in acquiring widespread press coverage of our activities with the autonomous vehicles. To date, the television stations that have covered field operations of this project include:
Fox 13 (Tampa), SNN (Sarasota), Channel 10 (Tampa), NBC 2 (Ft. Myers), Newschannel 8 (Tampa) and WWSB (Sarasota). Additionally, the following newspapers have printed articles: Sarasota Herald-Tribune, Pelican Press, Ft. Myers News-Press, Florida Today and the Anna Maria Island Sun. Though it is more technically oriented the journal Nature published an article in ScienceUpdate, January 23, 2003, that provided international coverge of the project. (see, http://www.nature.com/nsu/030120/030120-6.html).

Journal Publications

Kevin G. Sellner, Gregory J. Doucette, Gary J. Kirkpatrick, "Harmful algal blooms: causes, impacts and detection", J. Ind. Microbiol. Biotechnol., p. 383, vol. 30, (2003). Published,

Cheryl L. Dybas, "Harmful Algal Blooms: Biosensors Provide New Ways of Detecting and Monitoring Growing Threat in Coastal Waters", BioScience, p. 918, vol. 53:10, (2003). Published,

Books or Other One-time Publications

Oscar Schofield, Chris von Alt, "Making Progress on Harmful Algal Blooms: Lessons from the Gulf of Mexico", (2003). Workshop report, Published
Editor(s): D. L. Rudnick and M. J. Perry
Collection: ALPS: Autonomous and Lagrangian Platforms and Sensors, Workshop Report.
Bibliography: Geosciences Professional Services, Inc. 64 pp

Mark Moline and Gary Kirkpatrick, "Technology Advances: Autonomous Underwater Vehicles for Spatial Validation of Ocean Remote Sensing Products.", (2005). Workshop Report, Published
Editor(s): Oscar Schofield and Margaret K. Tivey
Collection: ORION: Ocean Research Interactive Observatory Networks
Bibliography: Geosciences Professional Services, Inc. 140 pp.

Oscar Schofield, Jennifer Bosch, Scott Glenn, Gary Kirkpatrick, John Kerfoot, Steve Lohrenz, Mark Moline, Matthew Oliver, and Paul Bissett, "Bio-Optics in Integrated Ocean Observing Networks: The Potential for Studying Harmful Algal Blooms", (2005). Book, Accepted
Editor(s): Marcel Babin, Collin Roesler, and John Cullen
Collection: Proceedings of the Workshop on Real-time Coastal Observing Systems for Ecosystem Dynamics and Harmful Algal Blooms
Bibliography: UNESCO series ?Monographs on oceanographic methodology?

Web/Internet Site

URL(s):
http://marine.rutgers.edu/cool/glider/florida/DailyFieldWork.html
Description:

Other Specific Products

Product Type:

Audio or video products

Product Description:
Underwater video of the Slocum gliders was collected on January 13 and 14, 2003 in coastal waters off Sarasota, Florida. This video is some of the first collected of Slocum gliders underwater in the marine environment.
Sharing Information:
Segments of these videos are available on the Rutgers University Coastal Ocean Observation Laboratory's website at: http://marine.rutgers.edu/cool/glider/florida/DailyFieldWork.html.

A public display of autonomous underwater vehicle technology is under development for the Mote Marine Aquarium. This display will feature these video products.

Product Type:

Data or databases

Product Description:
High-resolution data, including temperature, salinity, optical backscatter and chlorophyll fluorescence where collected during four autonomous underwater vehicle missions in the Gulf of Mexico from January 13 to January 16, 2003. Some of these data depict a weak frontal boundary between two water masses. These types of boundaries may be important to phytoplankton community interactions.
Sharing Information:
Figures of these data are posted on the Rutgers University, Coastal Ocean Observatory Laboratory website. Interpretation of the findings are being prepared for journal publication. The actual data will be made available to investigators who request it following publication.

Product Type:

Instruments or equipment developed

Product Description:

The optically-based phytoplankton discriminator has been reconfigured for installation in autonomous underwater vehicles. The basic instrument consists of components already describe in publications. The newly developed AUV payload instrument was significantly miniaturized and power consumption reduced relative to the prototype system. These changes required the development of a completely new embedded software control package.

Sharing Information:

This instrument should be generally applicable to any application in which the general taxonomic composition of the phytoplankton community is needed. There are certainly research aplications in both fresh and marine waters that could benefit from this instrument. Additionally there may be applications in aquaculture and municipal water supplies to detect noxious species.

Contributions

Contributions within Discipline:

The resulting systems have world-wide applicability to monitoring and study of phytoplankton communities in freshwater and marine systems. These instruments have value as stand-alone tools and as components of observation networks. Currently seven of these instruments are in service. Two are operating on autonomous underwater vehicles in coastal waters in New Jersey and California. Five instruments are deployed on channel markers, a bouy and a vertical profiler in the coastal waters of southwest Florida. Seven additional instruments are in production, 3 for AUVs and 4 for fixed installtions. This is one of the very first 'biologically oriented' instruments to be adapted to AUVs and incorporated in the coastal ocean observing system.

Contributions to Other Disciplines:

The potential of this approach for discriminating major classes of noxious algae (red, green, brown, and cyanobacteria) will directly contribute to decision making by both freshwater and marine water quality managers.

This system will complement the broader research community efforts to use satellite remote sensing techniques to monitor the distribution and taxonomic composition of phytoplankton communities.

Contributions to Human Resource Development:

The undergraduate and graduate students involved in this project have gained insight into the scientific principals and engineering considerations underlying these autonomous underwater vehicle technologies and their associated instrumentation. Since autonomous exploration will likely be a major component of future aquatic research and applied sciences it is critical that students be trained using this technology.

Contributions to Resources for Research and Education:

The success of this project has resulted in State and institutional support for the establishment of the Sarasota Operations of the Coastal Ocean Observation Laboratroy (SO COOL) at Mote Marine Laboratory. One of the major functions of SO COOL will be to serve as the control center for the network of OPDs to maintain their operation, collect their data, and integrate and interpret those data. Basic research (ecosystem studies) and applied research (harmful algae detection and tracking) will benefit from the newly available capability to remotely identify phytoplankton communities. The second major function of SO COOL is to provide education opportunities. These include distance learning programs, science teacher introduction to advance aquatic science technologies, environmental resource manager training on data products such as HAB distribution maps and public outreach through displays for the Mote Marine Aquarium and feeds to local television news (HAB distribution).

Contributions Beyond Science and Engineering:

This project is expected to contribute directly to public welfare by providing a means to detect and track harmful algal blooms. Utilizing the expected 'early warning' capability it will be possible to mitigate some of the harmful effects associated with red tide. A few examples of concerns that will benefit from increased warning time of red tide impact include reducing the possibility of consumption of contaminated shellfish, reducing contamination of aquaculture and aquarium operations, and reducing losses to tourism.

Categories for which nothing is reported:

Figure 1 Prototype shipboard Optically-based Phytoplankton Discriminator (OPD) (left). Miniaturized, reconfigured OPD payload for AUVs (right).

Figure 2 All-woman crew launch Slocum Glider during recent trials in the Gulf of Mexico.

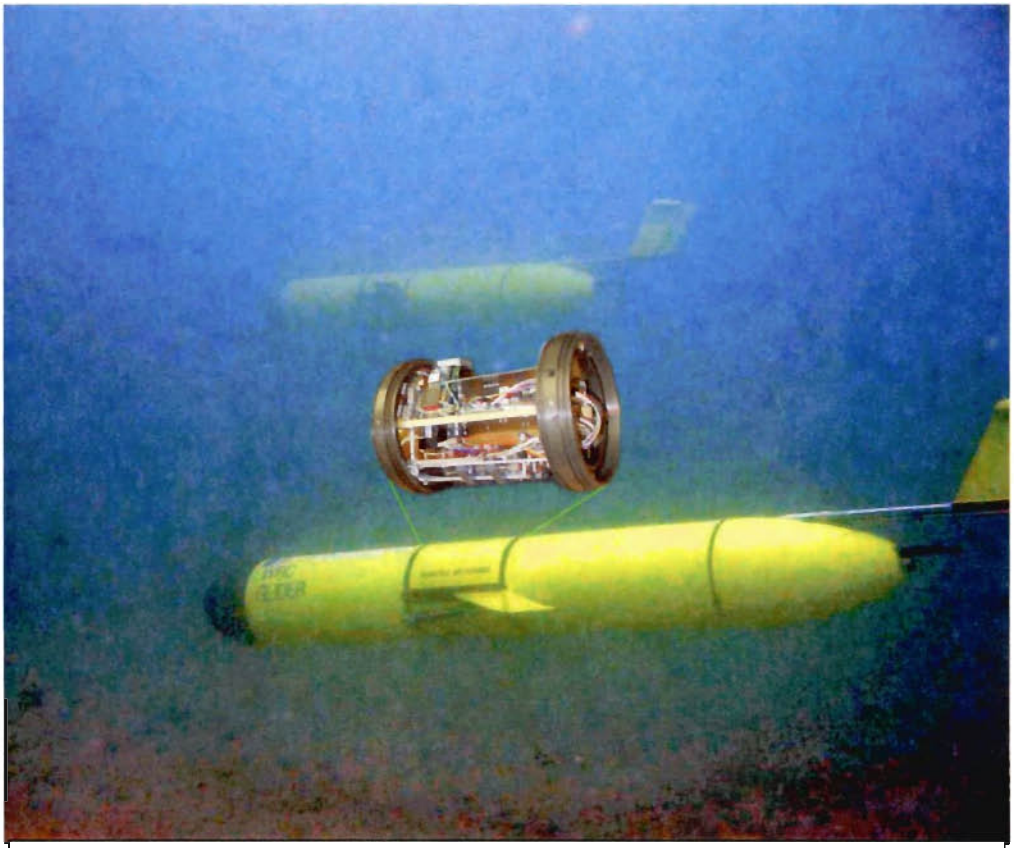

Figure 3 Slocum gliders during recent field trials in the Gulf of Mexico. Overlay of OPD (enlarged for illustration) emphasizes the combining of technologies to enhance undersea observation capabilities. Extension lines indicate the glider payload section where the OPD will be carried.

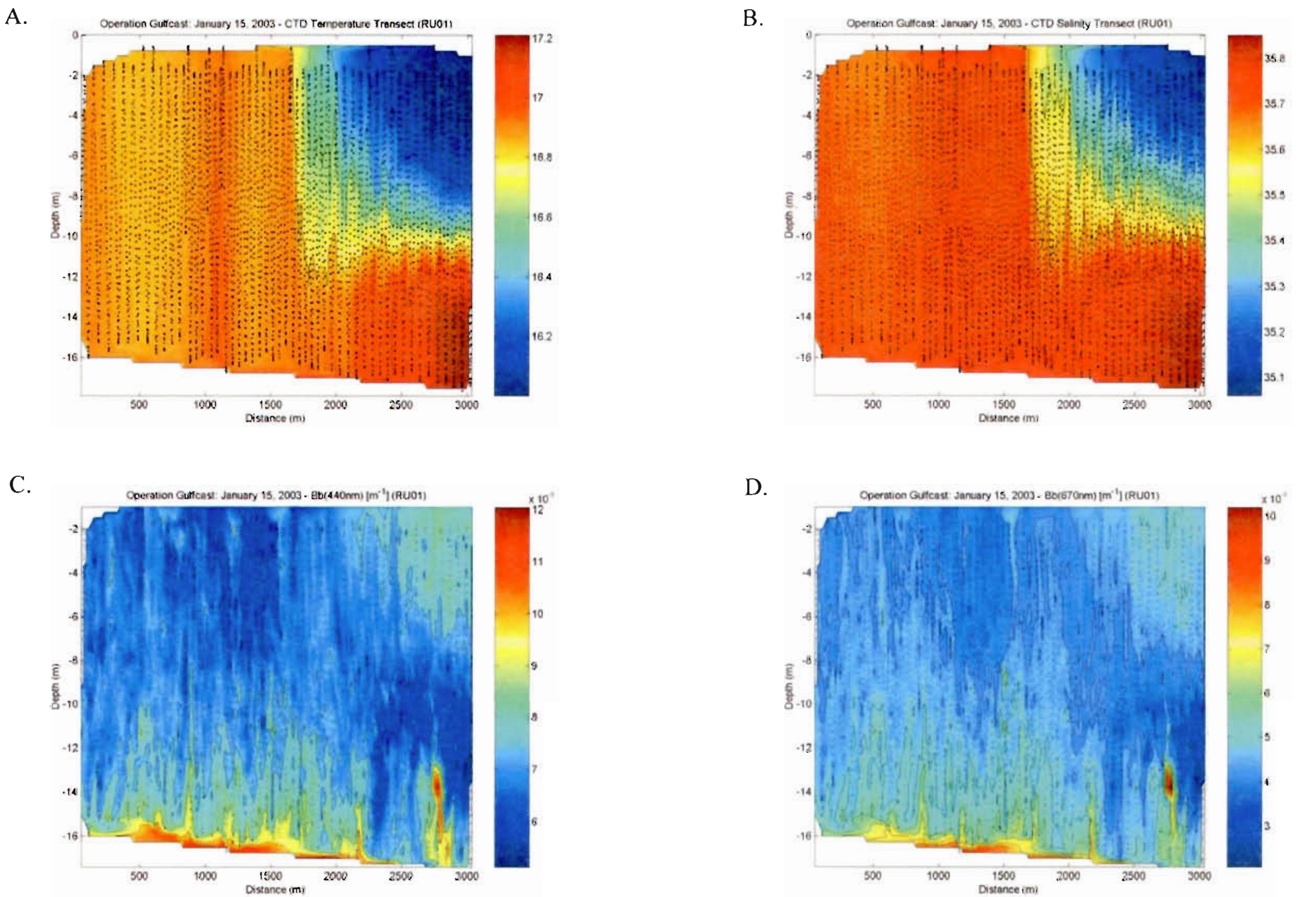

Figure 4 Cross sections of data collected during autonomous glider mission, Gulf Cast I, on January 15, 2003 in the Gulf of Mexico. Panel A is temperature, panel B is salinity, panel C is optical backscatter at 440 nm and panel D is optical backscatter at 670 nm. Dots are sample points.

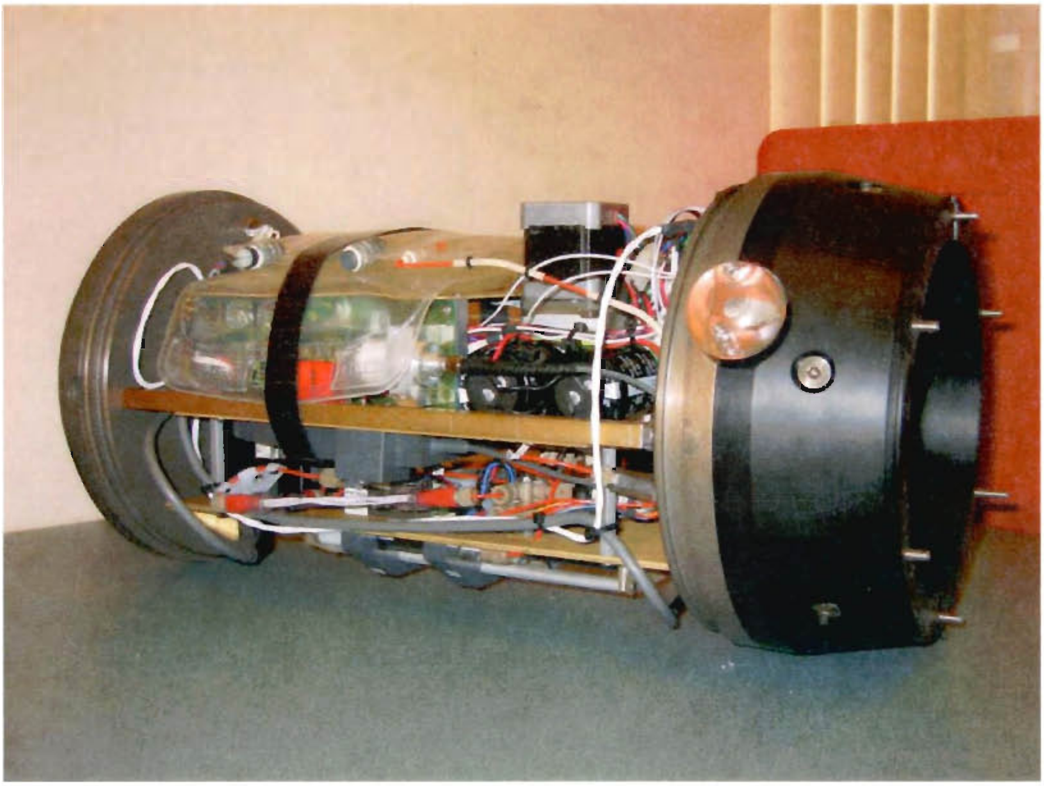

Figure 5 Latest version of the optical phytoplankton discriminator configured as a payload for the REMUS.

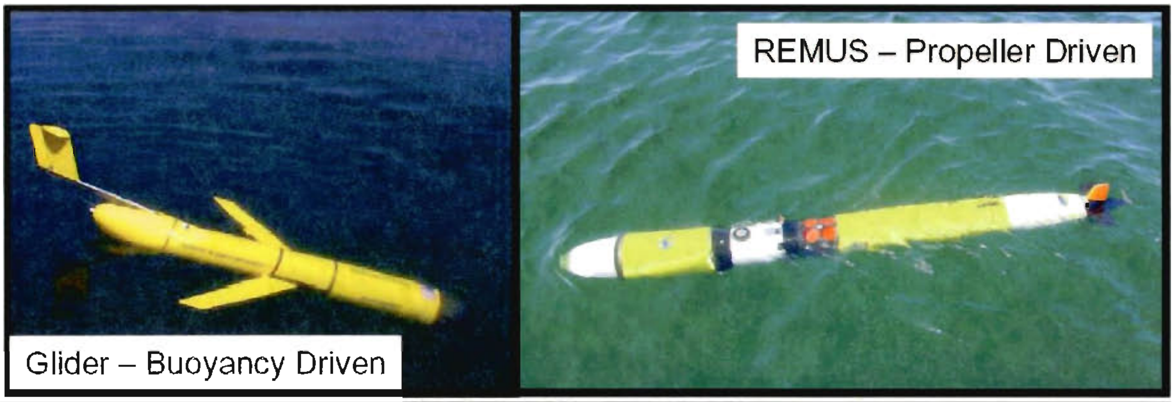

Figure 6. Buoyancy driven Webb Research glider (left) and propeller-driven REMUS AUV (right) shown during deployments on the West Florida Shelf in November 2003. The HAB detection instrument is integrated into the glider in the center section, where the wings are attached to the body. In the REMUS, the HAB instrument is the yellow section aft of the white nose section. The nominal operational speeds of the AUVs are 0.4 m/sec and 2.5 m/sec for the glider and REMUS, respectively.

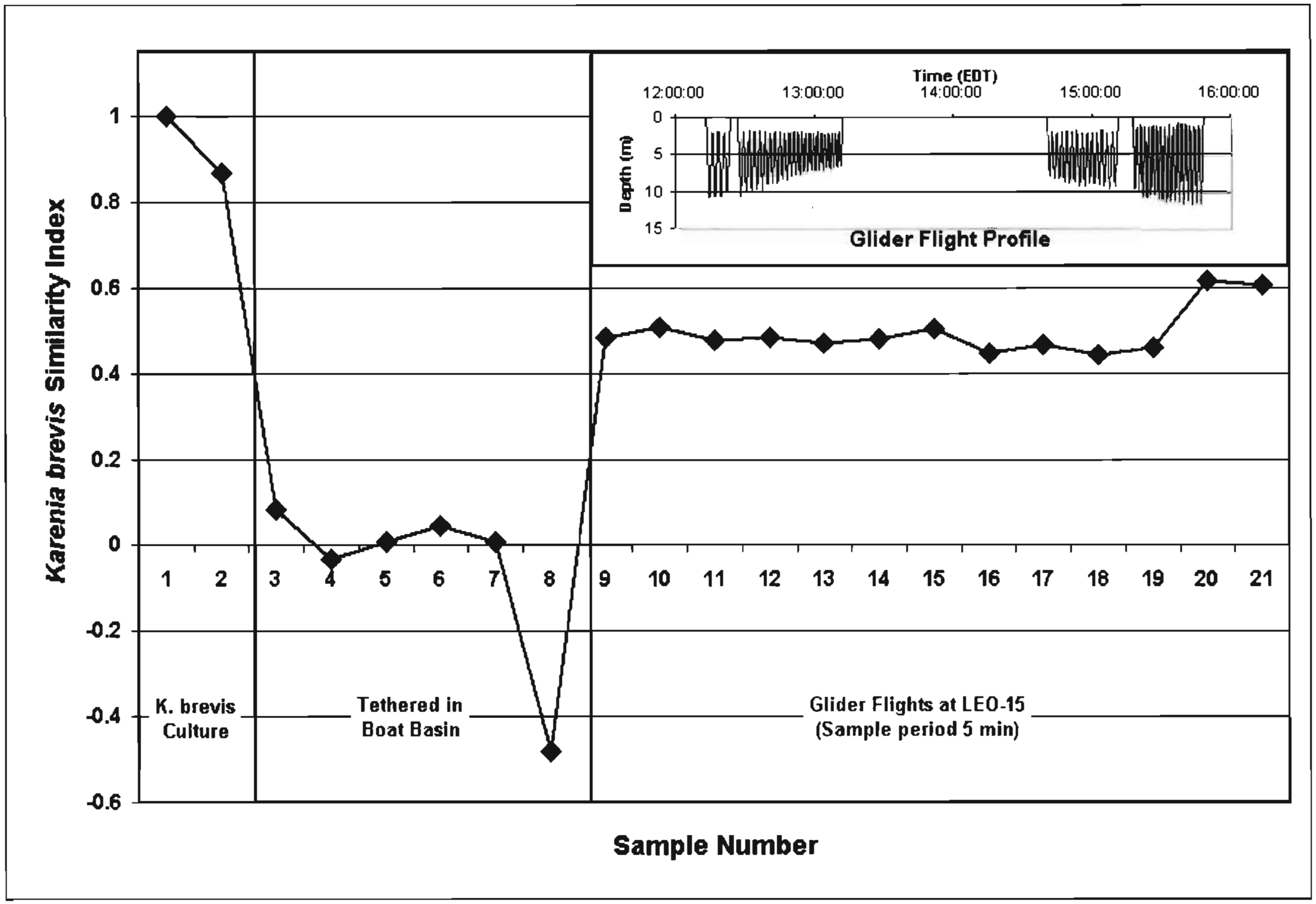

Figure 7 First phytoplankton similarity index results from an open ocean deployment of a Webb Glider fitted with an OPD on May 19, 2003. First two samples were culture samples of *Karenia brevis*. The middle six reading were made during a checkout dive in the boat basin of the Rutgers University field station in Tuckerton, NJ. The 13 samples to the right were made while the AUV was swimming a mission approximately 10 km off the coast at the LEO-15 site.

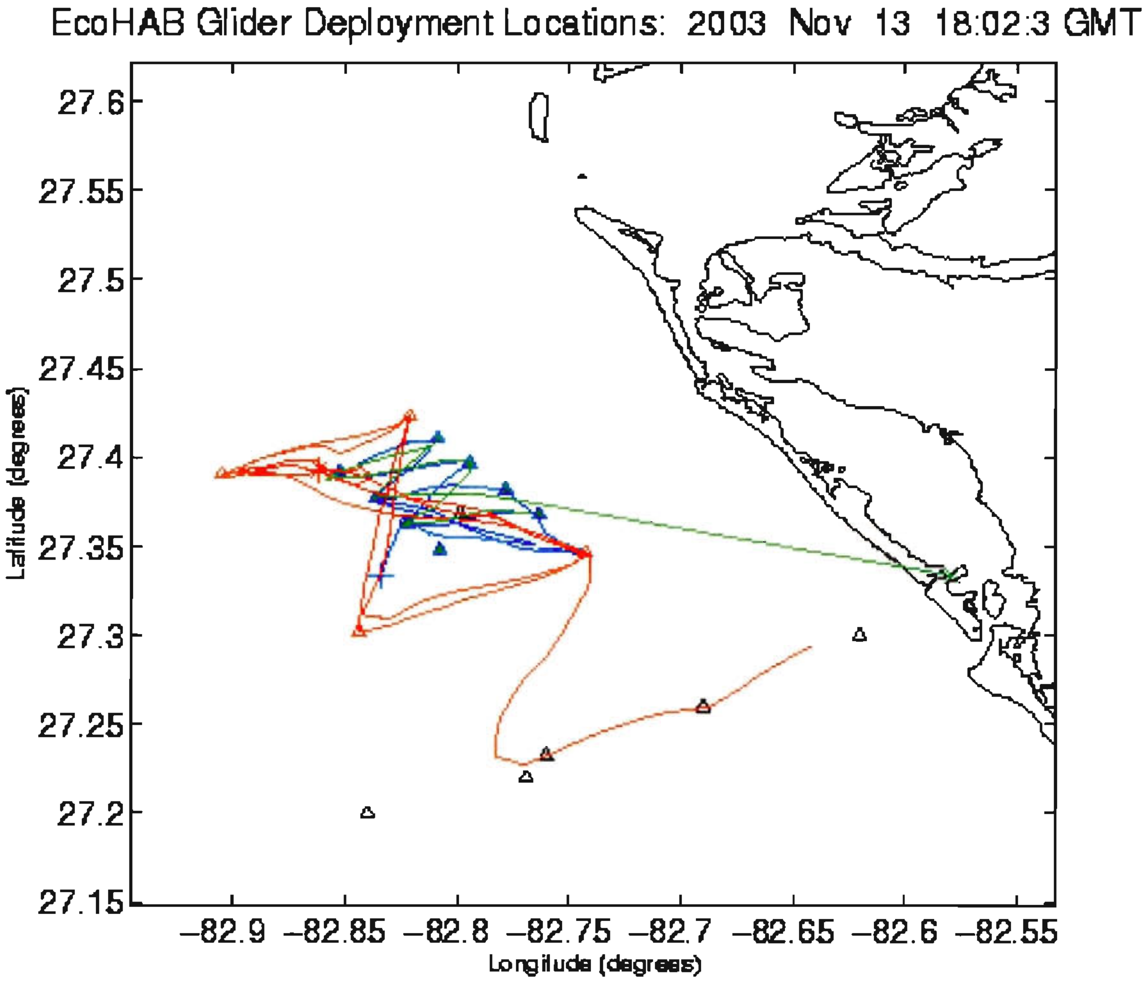

Figure 8 Tracks of three Webb electric gliders during Gulfcast III, November 12-14, 2003 just south of the mouth of Tampa Bay. Not shown in this figure is the nested track of the REMUS operated simultaneously with the gliders.

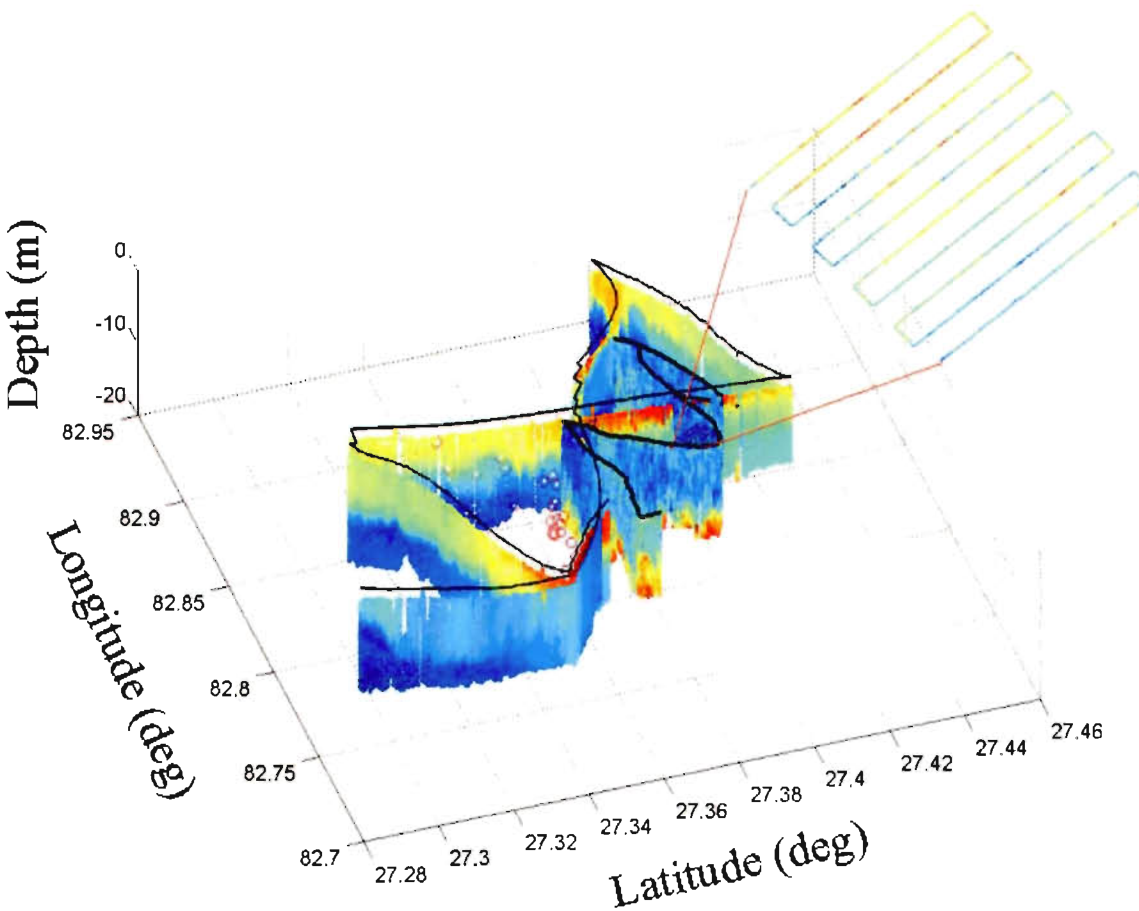

Figure 9. Embedded data volume collected from 3 gliders and 1 REMUS AUV offshore of Sarasota, FL in November 2003. Vehicle tracks are highlighted at the surface in black. The "figure-8" path of one of the gliders (line black line) shows the stratified temperature contours on the shelf. A second glider (thick black line), weaved through the previous glider track, showing depth contours of attenuation at 530nm. The third glider outfitted with the HAB detection instrument also flew through the same volume measuring the similarity index of *K brevis* (indices > 0.30 are highlighted with a red open circle). In addition to the gliders, a REMUS AUV systematically measures the reflectance ratio of 490nm/550nm within a grid. Although data rich, this figure demonstrates the diversity of sensor payloads currently being deployed and the utility of this nested approach in defining the environmental conditions required to develop and maintain HABs off the coast of Florida.

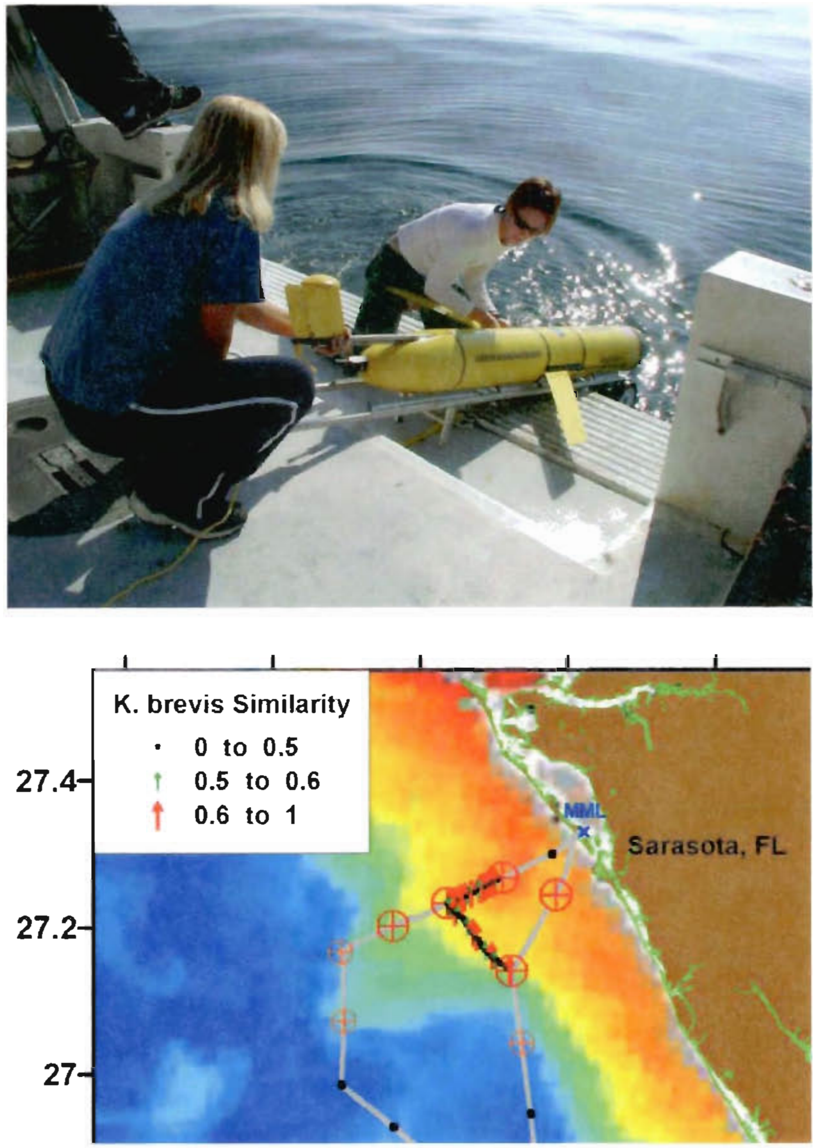

Figure 10 A Webb electric glider being launched (top panel) approximately 8 km offshore of Sarasota, Florida to investigate the distribution of a *Karenia brevis* bloom on Jan 15, 2004. The mission track is shown in the lower panel superimposed on a satellite image (colored background) of chlorophyll distribution for that day. The grey track is the survey track of the vessel that launched the glider and then recovered it at the end of the mission.

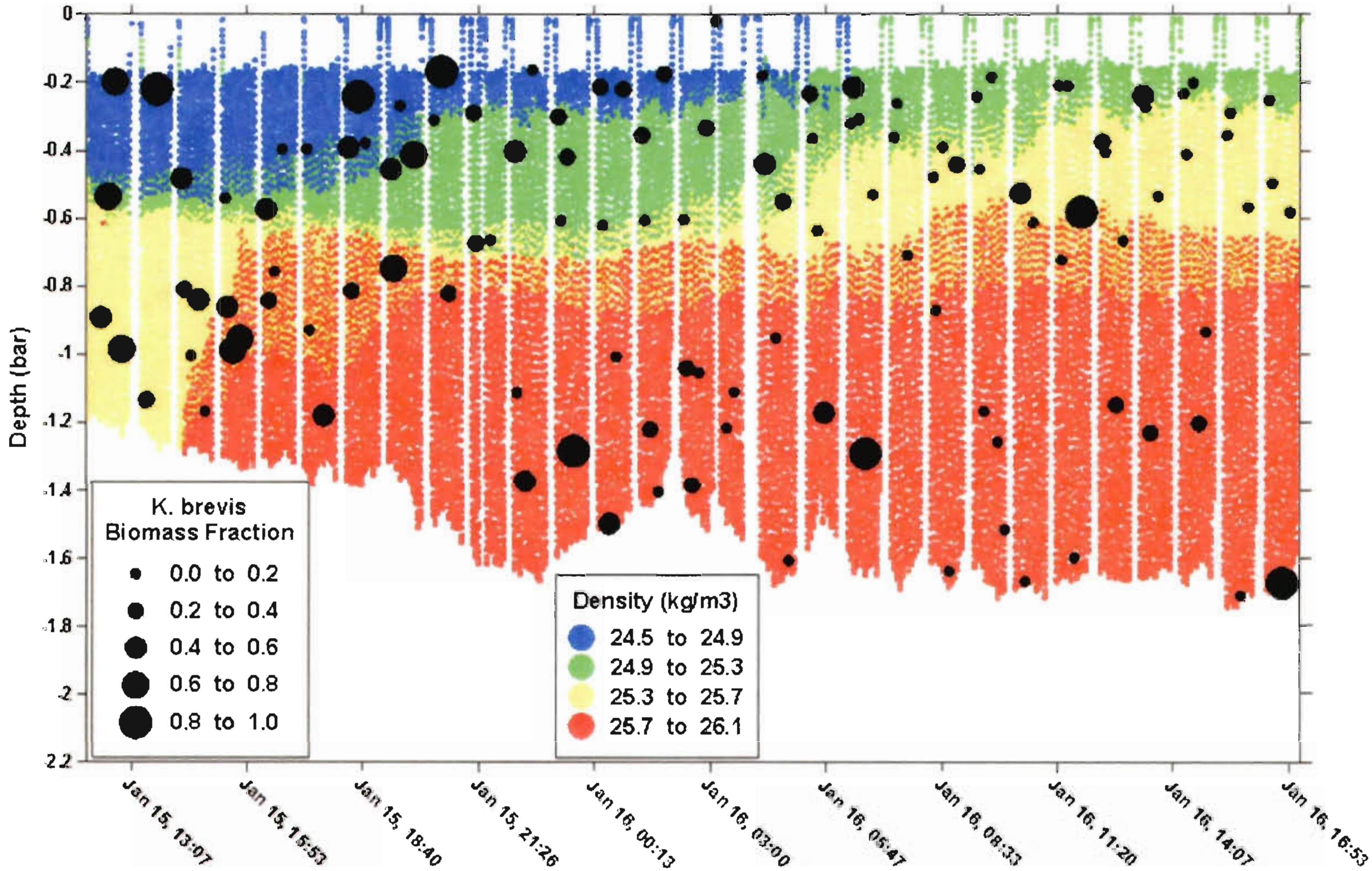

Figure 11 Vertical cross-section of water density (sigma-t) measured by the Webb electric glider equipped with an OPD shown in figure 10 being launched on a survey mission in a bloom of *Karenia brevis* in Jan 2004. The biomass fraction of *K. brevis* measured by the OPD is overlain on the density field. Note that the density field was not produced by a contouring routine, but is a field of actual density measurements (approximately 44,000).

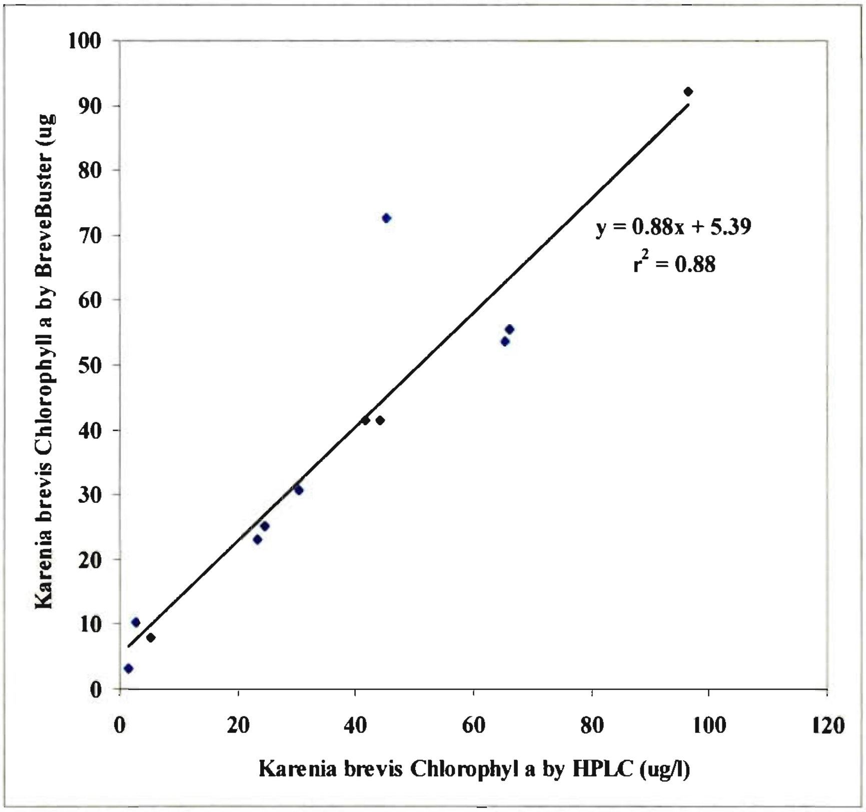

Figure 12 **BreveBuster-estimated chlorophyll a contributed by *Karenia brevis* in mixes of cultures compared to high-performance liquid chromatography determinations of the *K. brevis* contribution of chlorophyll a. Species included in the mixes were *Tetraselmis impellucida*, *Gyrodinium instriatum* and *Dactyliosolen fragilissimus*.**

GulfCast IV: September 28, 2004 – October 7, 2004

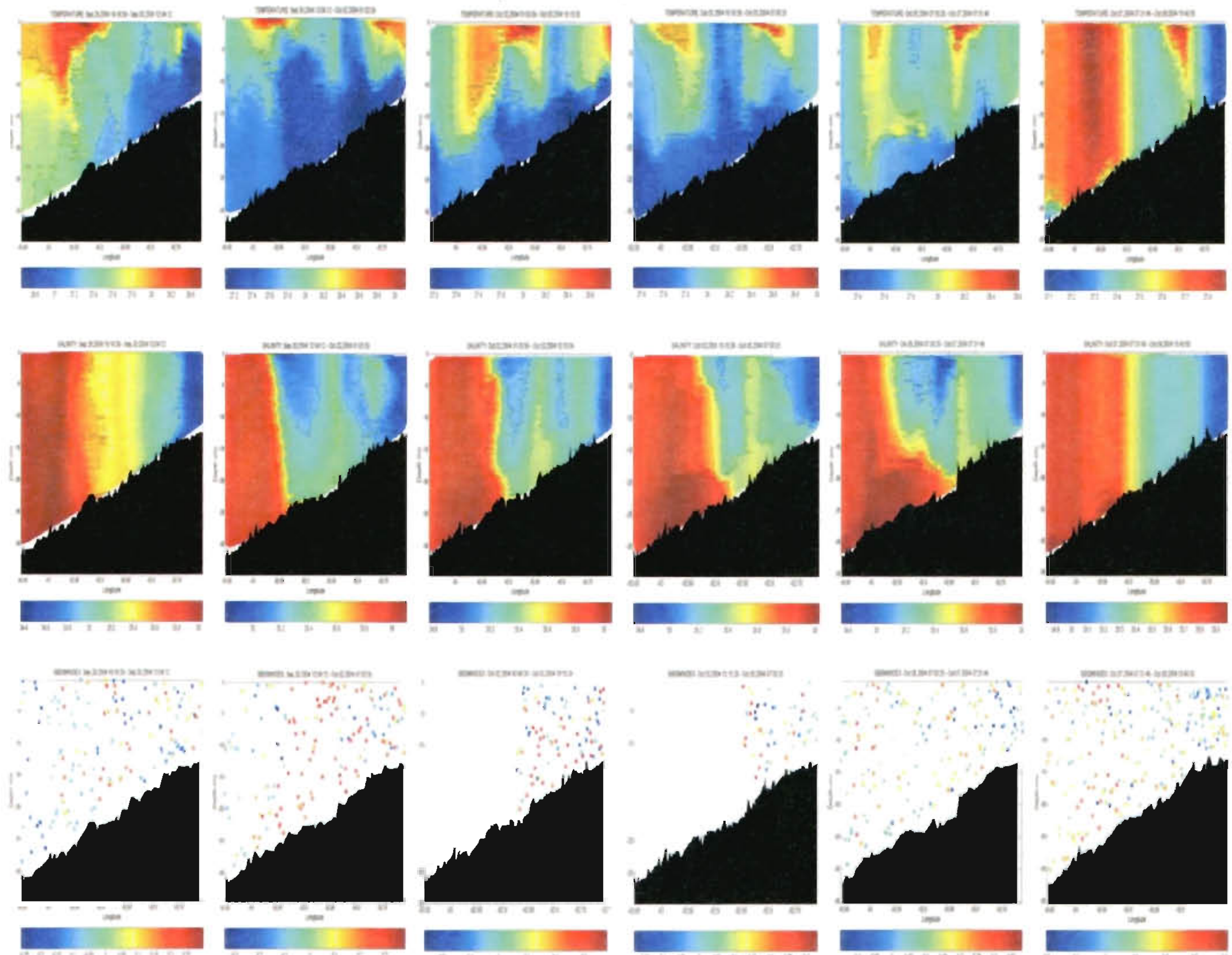

Figure 13 **Cross sections of temperature (top row of panels), sigma-t (middle row of panels and *Karenia brevis* similarity index (bottom row of panels) collected by the OPD-equipped Webb glider from September 28 to October 7, 2004. The transects run along a line perpendicular to the coast off Sarasota, Florida between the 10 and 30 meter isobaths. Note that all similarity indexes are below the *K. brevis* threshold of 0.6 indicating there was no *K. brevis* detected during this mission.**

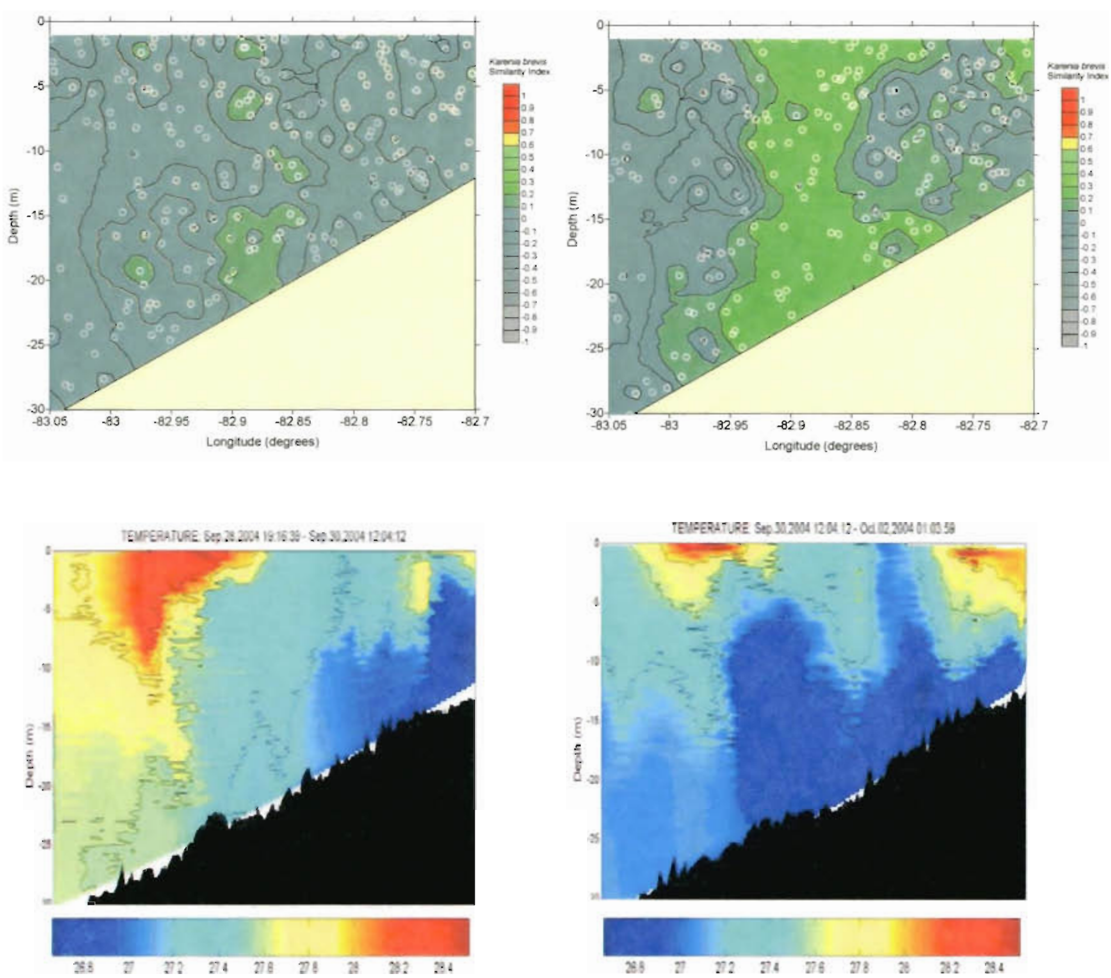

Figure 14 Comparison of OPD similarity indices (top panels) to temperature structure (lower panels) during two transits of the line offshore of Sarasota, Florida introduced in figure 11. There were no high similarity indices indicating the lack of the target species, *Karenia brevis*. However, the contours of the similarity indices show that the phytoplankton community was not homogeneous and changed apparently in response to a physical event that changed the temperature structure of the water column.

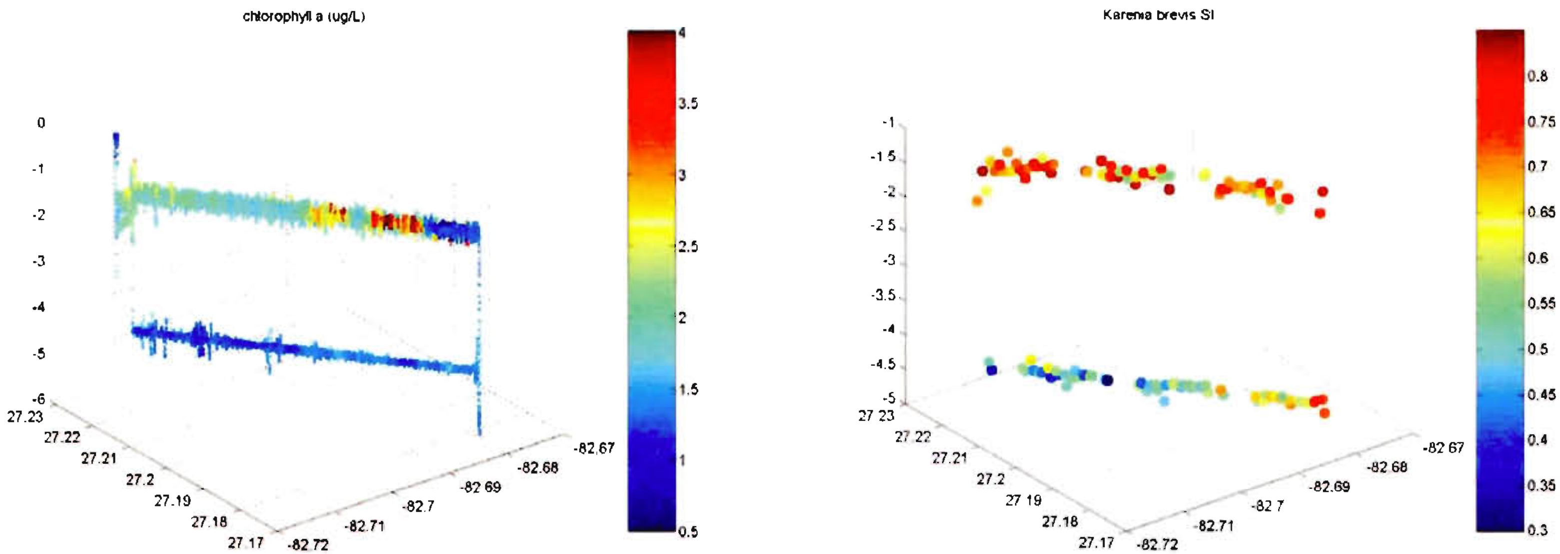

Figure 15 Chlorophyll fluorescence (left panel) and *Karenia brevis* similarity index (right panel) measure by a REMUS AUV fitted with an OPD on January 21, 2005. The vehicle was operating in a *K. brevis* bloom that was concentrated near the surface of the water.