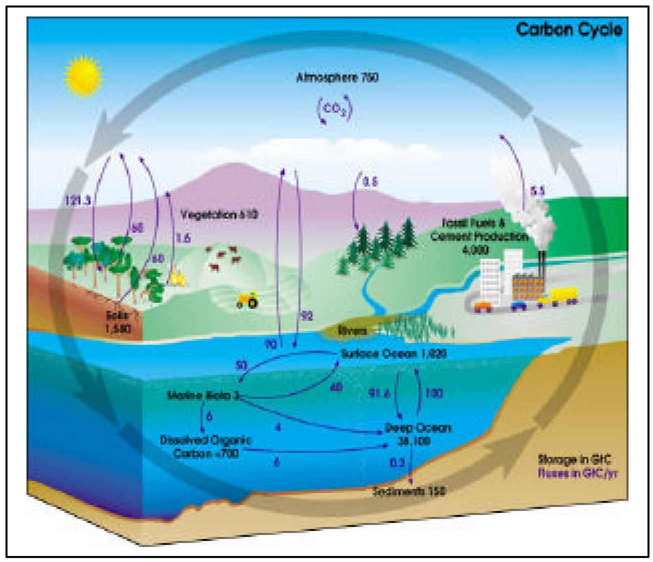
Coastal Ocean Carbon Observations and Applications (COCOA)

The COCOA mission concept provides a solution to the critical problem of quantifying the pools and fluxes of carbon in the coastal ocean, knowledge of which is essential for understanding the role of the global carbon cycle in climate variability and change.

COCOA Mission Concept

The COCOA end-to-end suite of measurements will be accomplished through the synergistic use of high-resolution spectral reflectance data from a high-precision, hyperspectral imager in geostationary orbit (GEO), coupled with complementary satellite and field measurements, and integrated within a modeling framework. This system of integrated observations and models will discriminate and quantify particulate and dissolved carbon species in coastal waters, as well as the exchanges of carbon between the land, atmosphere, and ocean. The geostationary vantage point provides the sampling frequency needed to resolve dynamic processes in coastal regions which are dominated by tides and winds. It has the added advantage of mitigating losses due to cloud cover and fog. By intensively focusing on North America, COCOA will accurately quantify representative coastal processes that impact the global carbon cycle: Western Boundary Currents (Gulf Stream), Eastern Boundary Currents and coastal upwelling (California Current), major riverine inputs (Mississippi River), and episodic features (storms, blooms).



Visible Spectral Radiance (VSR) Measurements

The specific COCOA measurement approach from space is to collect high-precision visible spectral radiance (VSR) data (350-1050 nm coverage with 5 nm resolution) at 200 m ground resolution (at nadir) at sub-diurnal frequency. Ground resolution at the northernmost part of the domain will range from 250 m (Gulf of Mexico) to 300 m (Gulf of Maine). The COCOA spectrometer is based upon existing space-proven charge sensors which have low intrinsic noise (between 20 and 40 electrons root-mean-square) ensuring signal shot noise is the only limiting factor for the sensed signal.

The COCOA instrument is compact and the sensors have small pixel sizes. From a geostationary altitude, a ground sample instantaneous field of view of 200 m corresponds to an angular field of view of ~3 arcsecond, which will be provided by a moderate telescope aperture of ~0.5m. Numerous examples of ~0.5 m class telescopes have been flown by NASA over the past decade (e.g., HST, WIRE, SPITZER, GALAX). The polarization sensitivity is less than 0.5 %. Since the required instantaneous field is significantly less than 1 degree, a simple two-mirror telescope system can be accommodated with reduced scattering. The pointing and scanning requirements, although stringent, can be achieved with currently available spacecraft.

COCOA Instrument Description and Performance	
Optics	F/5 Cassegrain telescope and Offner Spectrometer
Focal Plane Array	Visible CMOS/CCD detector
Primary Mirror	~ 50 cm diameter
Mass / Power	71 kg / 50 W
Spatial Sample at Nadir	200 m
Spectral Sample	5 nm between 350 and 1050 nm
SNR	600 to 1000 between 400 and 800 nm at 10 nm

Absolute calibration accuracies are commensurate with state-of-the-art calibration methodologies (i.e., vicarious and on-orbit). The relative accuracy will be the same as the radiometric precision: the nominal radiometric precision will be between 500 - 1000:1 for each 5 nm band at 200 m spatial sampling. Since COCOA is in a geostationary orbit the imager can look for long periods and obtain even higher radiometric precision through long integration times. These capabilities far exceed any orbiting spacecraft in LEO, MEO or GEO.

Data Inversion and Algorithm Development

COCOA will utilize a modeling framework to derive coastal fluxes and pools from VSR measurements. The VSR will be inverted to provide both the atmospheric correction and the concentrations of key optical constituents, namely chlorophyll, suspended and dissolved matter. The concentration of particulate inorganic carbon (PIC), particulate organic carbon (POC), dissolved inorganic carbon (DIC) and dissolved inorganic carbon (DOC) will be estimated from regionally-specific algorithms where necessary. Complete knowledge of carbon pools and pathways will then be determined by assimilation of these concentrations into coupled biological-physical models. In this respect, COCOA will benefit from the work currently pioneered by Watson Gregg (NASA GSFC) under a NASA REASoN CAN ("Ocean Color Time-Series Project") that assimilates satellite data into a global-scale biogeochemical model. The COCOA science team will implement a similar approach using regional-scale models for the West Coast, Gulf of Mexico, and East Coast.

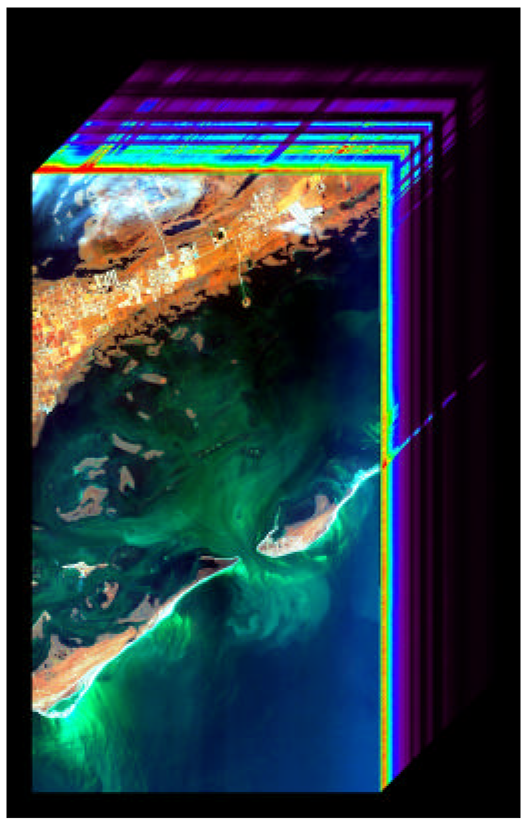
COCOA's approach to atmospheric correction will address the challenge inherent to atmospherically complex coastal regions. The GEO platform enables multiple repeat samples and long viewing opportunities. The small pixel size will maximize viewing opportunities as well as help improve atmospheric characterization. The broad spectral range (particularly into the UV) and high spectral resolution will enable optimal algorithm development that will employ state of the art inversion techniques. A concerted effort to improve aerosol characterization will be made, taking advantage of ground-based measurements and knowledge of air mass circulation and characterization. Recent studies have shown it is possible to derive three-dimensional aerosol distributions over the ocean through assimilation of data from several satellites (TOMS, MODIS) and ground-based networks (AERONET) into models (Da Silva, 2005).

With respect to the inversion algorithms, COCOA will leverage and benefit from several research activities related to the differentiation of carbon species and fluxes. Algorithms for particulate species (PIC and POC), and for colored dissolved organic carbon (CDOM), are currently being evaluated by the NASA MODIS Ocean Science Team with plans to implement these as standard products in the near future. The concentration of DIC and of CDOM is also underway under the auspices of NASA's Carbon Cycle Science program. The relationship of CDOM to DOC is presently being modeled on regional, site-specific bases.

Calibration and validation of COCOA's measured and modeled carbon pathways and pools will benefit from *in situ* physical and biogeochemical observational capabilities associated with the developing national Integrated Ocean Observing System (IOOS) as well as other evolving coastal observing systems, including the NSF ORION program. These field measurements will provide coastal calibration/validation support, as well as insights into subsurface dynamics that cannot be acquired through space-borne measurements.

COCOA Advances Earth Sciences

The coastal ocean is an important component of the global ocean carbon cycle. About 25-50% of the global marine photosynthesis occurs in the coastal ocean (Muller-Karger, 2001), although the coastal zone only represents 10% of the global ocean. Estimates of export production in the coastal zone range from 30% (Karl et al., 1996) to 80% (Walsh, 1991) of the global value. The carbon flux from land to ocean can be significant: riverine flux to the coastal ocean of the United States is 10-30% of the atmosphere-land carbon flux (Pacala, 2001).



AVIRIS image cube highlighting the complexity of coastal processes.

Carbon fixed through photosynthesis in the coastal ocean is strongly influenced by complex physical and biological controls on nutrient supply and light availability. The air-sea exchange of carbon dioxide depends on both physical transport processes in the atmosphere and ocean as well biological uptake. Carbon exchange between the continental margin and the deep-sea (including land-to-ocean transport of carbon) is poorly understood because it is often small and when larger, takes place episodically. The uncertainty associated to these and other estimates are large, indicating our lack of understanding and knowledge.

As a result, key questions still remain as to whether coastal regions represent an overall net source or sink for atmospheric CO_2 over a year (Ianson & Allen, 2002).

Because of the considerable temporal and spatial variability, as well as the heterogeneity of coastal regions, quantifying the carbon pathways and flux in the coastal zone is one of the most challenging scientific problems of the global carbon budget. The deficiencies in our understanding of these processes primarily result from inadequate observing capabilities. These dynamic regions are at the interface of the oceanic, terrestrial and atmospheric domains. Coastal zones are difficult to observe as they exhibit extreme environmental heterogeneity. Existing NASA/NOAA polar orbiting platforms/sensors are not capable of resolving the large observed temporal, spatial, and ecological gradients

Temporal complexity: Coastal processes and phenomena (e.g., eddies, harmful algal blooms) are dynamic and ephemeral, often exhibiting considerable variability on sub-diurnal time scales. Multiple sensor-looks per day are required to capture these changes and, can additionally remove tidal aliasing and mitigate cloud cover. Conversely, current ocean viewing satellites provide, at best, once daily temporal revisits.

Optical complexity: Coastal (Case 2) waters are optically complex, with optical constituents that include phytoplankton pigments, colored dissolved organic material (CDOM), and suspended sediments. Spectroscopy is required to accurately discriminate between these water column constituents and atmospheric constituents (e.g., aerosols) that affect retrieval of geophysical parameters relevant to the carbon cycle. Current generation ocean color satellite sensors typically provide fewer than 20 broad optical bands while COCOA will provide 140.

Spatial complexity: Coastal processes and phenomena are often characterized by variability on the order of hundreds of meters to a few kilometers in horizontal extent. Such spatial scales cannot be adequately resolved with the current generation of ocean color satellite sensors, which generally have a ground resolution on the order of 1 km.

In order to better assess, understand and predict natural and anthropogenic-driven physical and biogeochemical variability in coastal zones, particularly towards improved quantification of carbon pathways, the U.S. coastal carbon science community have requested a dedicated coastal carbon imager with high temporal coverage (sub-diurnal), spectral resolution (>>20 bands with narrow bandwidth) spatial resolution (< 1km). The COCOA mission will meet these needs, in particular providing 200 m ground resolution at nadir. By contrast, the spatial resolution of most current ocean color sensors is at best ~1km.

COCOA as pathfinder: COCOA will be the pathfinder for the next generation of operational, geostationary imagers. In addition to developing the algorithms for quantifying carbon pools and fluxes, the mission will explore coastal processes and applications that can not be observed with the current generation of satellites, for example harmful algae blooms (HABS), hurricanes, coastal upwelling and coastal management.

COCOA Mission Cost

Extensive mission design studies have been undertaken at JPL on the COCOA concept. Employing NASA cost-estimating and parametric-modeling tools to produce a quantitative cost-model-analysis, the COCOA mission concept is estimated to cost just over $200M. This costing includes 30% reserve for mission phases A through D and 15 % reserve for phase E. According to the classification outlined in the "NRC Decadal Study Request for Information", COCOA is anticipated to fit into the category of "medium-size" class mission.

COCOA Mission Description	
Payload	Imaging Spectrometer
Spacecraft Bus	RSDO catalog bus
Launch Vehicle	Delta II – 7425/3-Stage & Kick Stage
Mass / Power	71 kg / 50 W
Mission Duration	2 Years
Orbit	Geostationary
S/C & Instrument Mass	368 kg (30% cont + 18% margin)
S/C & Instrument Power	386 W (30% cont + 250% margin)
Mission Cost	~$200M

COCOA is a High Priority Mission

A Critical Need by the Community

Improved measurements of the coastal zone have been identified by the science communities that focus on ocean color, biogeochemistry, and carbon cycle research, as well as being part of NASA's strategic plan for Earth Science.

In the Strategic Plan for the U.S. Integrated Earth Observation System (CENR/IWGEO, 2005), coastal regions have been identified as a priority area. In particular, there is a specific call-out for COCOA-type ocean color measurements in support of the Ocean, Climate, Human Health, and Ecology societal benefit areas. Likewise, in the Global Earth Observing System of Systems (GEOSS) Implementation Plan (GEO, 2005), COCOA will support the thrust areas of Climate, Ecosystems, Biodiversity, Agriculture and Energy.

The International Ocean Color Coordinating Group (IOCCG), comprised of international experts in the field of satellite ocean color, has also identified the need for significantly improved coastal ocean color observing capabilities in terms of *temporal* (sub-diurnal => geostationary), *spectral* (more bands & finer bandwidth to discriminate optically complex coastal waters and improve atmospheric corrections => hyperspectral), and *spatial* (~100 - 500 m ground resolution needed) coverage and resolution, as well as improved signal to noise ratio (SNR) (see: IOCCG, 1999; IOCCG, 1999; IOCCG, 2000).

Chapter two of the NASA Earth Science Enterprise (ESE) Research Strategy on "Biology and biogeochemistry of ecosystems and the global carbon cycle" has identified the need for both hyperspectral and geostationary measurements in coastal zones to address carbon cycle issues as well as for application needs (e.g., harmful algal bloom detection). Additionally, the current NASA roadmap for Carbon Cycle and Ecosystems specifically calls out the need for a coastal carbon mission to reduce flux uncertainties and address coastal carbon dynamics.

Future plans within the *U.S. Carbon Cycle Science Program* highlight the need for high-resolution, broad spatial coverage of biomass, biological productivity and carbon fluxes in the coastal zone (Sarmiento & Wofsy, 1999). The implementation strategy for ocean carbon science (Doney, et al. 2004) highlights the importance of the coastal carbon cycle. The North American Carbon Program specifically calls for intensive sampling along the coast of North America (Wofsy and Harriss, 2002). The spatial range and temporal and spatial resolution require either aircraft or geostationary platforms to provide the necessary coverage.

Finally, COCOA type measurement capabilities and anticipated science returns have also been identified as a priority by the Coastal Theme Report of the Integrated Global Observing Strategy (DiGiacomo and McManus, 2005); the first Annual Integrated Ocean Observing System (IOOS) Development Plan (NOPP, 2005); the IGBP Integrated Marine Biogeochemistry and Ecosystem Research (IMBER) Science Plan and Implementation Strategy (Hall, 2005), the IGBP Land-Ocean Interactions in the Coastal Zone (LOICZ) II Science Plan and Implementation Strategy (Kremer et al., 2005), and Coastal Observatory Research Arrays: A Framework for Implementation Planning (Jahnke et al., 2003).

Contribution to the NRC Decadal Study Panels, Earth Sciences and Society

COCOA will contribute to the panel theme on "Climate Variability and Change" by improving greater understanding of climate variability through quantification of the role of the coastal ocean in the global carbon cycle. However, it will also make significant contributions to the "Land-use Change, Ecosystem Dynamics, and Biodiversity" by providing insights into coastal phytoplankton dynamics and taxonomic assemblages. Finally, it will also contribute to "Earth Science Applications and Societal Needs" by providing better understanding of complex coastal processes and phenomena, including impact of storm events and riverine inputs as well as development of harmful algal blooms. Further, we anticipate COCOA will provide support for more timely and effective decision-making in coastal regions towards improved coastal management. In particular, as part of an anticipated partnership with NOAA, some of the COCOA data stream could be made available in real-time as part of a "bent-pipe" design to support NOAA monitoring and tracking of pollutant-laden storm-water runoff plumes, harmful algal blooms, and other coastal hazards. Information from COCOA could help support beach closure decisions, closures of shellfish beds, and other priority needs.

Contribution to Long-Term Monitoring of the Earth

The COCOA mission, with its state-of-the-art instrument, carbon-specific algorithms and models will contribute to long-term monitoring of the Earth. This will be accomplished through development of coupled, validated, highly resolved physical-biogeochemical models addressing coastal ocean carbon flux, as well as serving as a pathfinder for future GEO missions. Regarding the latter, COCOA will support implementation of the operational coastal water imagers currently planned for future GOES platforms. In particular, the NOAA Coastal Water imager (CWI) will likely be part of the Hyperspectral Environmental Suite (HES) on GOES-R that also includes a sounder. Despite the name "hyperspectral," the HES-CWI is in fact a multispectral instrument. It has 14 spectral bands and less radiometric precision than given in COCOA's specifications. HES-CW's spatial resolution (300 m at nadir), spectral resolution (nominally 20 nm) and range (no UV bands), and temporal resolution is also coarser.

HES-CWI will excel in meeting its operational objectives; it is not, however, a dedicated coastal carbon mission designed with research requirements as the primary driver – hence the need for COCOA. In this context, COCOA will support the transition from research to operations and help define band selection and develop models/algorithms and a robust cal/val strategy for future operational multi-spectral coastal ocean imagers, e.g., HES-CWI, in support of routine coastal monitoring.

Readiness Level

A COCOA science team was established in 2003. The 20 team-members are internationally recognized experts in coastal and carbon cycle science, as well as in algorithm and model development, and come from universities, Navy, NASA, and NOAA laboratories. This team has been working with engineers and technologists at the Jet Propulsion Laboratory in designing the COCOA concept and is committed to its realization.

The COCOA concept leverages NASA's experience with imaging spectroscopy and moderate size space borne telescopes. Moreover, NASA has significant experience with providing integrated mission system comparable in complexity to the COCOA mission concept. The subsystem technologies that will be employed by the COCOA mission range between 7 and 9 on the NASA technology readiness level (TRL). A TRL of 7 is assigned to systems that are still prototypes, but demonstrated in a space environment, and a TRL 9 is assigned to a system that is flight proven through successful mission operations.

Risk Mitigation

The COCOA mission concept is a pathfinder for the next decade of earth observations from geostationary orbit. In the broadest context it will be a pathfinder for science missions from higher vistas, which in turn enable high frequency measurements of rapidly evolving systems with unprecedented sensitivity. COCOA will also be a pathfinder in its mission concept of full integration with other data streams and with coupled physical-biogeochemical models. Specifically, COCOA will provide a measurement capability for future earth studies that aim to integrate complex systems and modeling frameworks. The COCOA mission will provide high quality visible imagery of the Americas as required to support the national and scientific interest.

Synergies with Other National/International Observing Systems and Plans

The COCOA mission will complement the continuing development of a number of national and international coastal observing systems. These efforts are described in a number of recent reports including: The first Annual Integrated Ocean Observing System (IOOS) Development Plan (NOPP, 2005); Integrated Strategic Design Plan for the Coastal Ocean Observations Module of the Global Ocean Observing System (GOOS) (UNESCO, 2003); Coastal GTOS Strategic Design and Phase I Implementation (FAO, 2005); the IGBP Land-Ocean Interactions in the Coastal Zone (LOICZ) II Science Plan and Implementation Strategy (Kremer et al., 2005); the Coastal Theme Report of the Integrated Global Observing Strategy (DiGiacomo and McManus, 2005); and Coastal Observatory Research Arrays: A Framework for Implementation Planning (Jahnke et al., 2003). Many of the above reports and implementation plans predominantly focus on *in* *situ* observations and networks, and they also call out the need for COCOA-type satellite observations to address coastal ecosystem dynamics. In this context, COCOA intends on complementing, leveraging and integrating these planned *in situ* and ground-based observing networks to address coastal carbon cycle dynamics.

References

CENR/IWGEO. 2005. *Strategic Plan for the U.S. Integrated Earth Observation System*, National Science and Technology Council Committee on Environment and Natural Resources, Washington, DC.

Da Silva, A. 2005. MODIS Science Team Meeting: http://modis.gsfc.nasa.gov/sci_team/meetings/200503/plenary.html

DiGiacomo, P.M., and L. McManus. 2005. *The Coastal Theme Report of the Integrated Global Observing Strategy*, IGOS Partners, http://ioc.unesco.org/igospartners/coastal.htm

Doney S., et al. 2004. *Ocean Carbon and Climate Change: an implementation strategy for U.S. Ocean Carbon Research*, UCAR, Colorado. 108 pp.

FAO. 2005. *Coastal GTOS Draft Strategic design and phase 1 implementation plan*. By Christian, R.R., Baird, D., Bowen, R.E., Clark, D.M., DiGiacomo, P.M., de Mora, S., Jiménez, J., Kineman, J., Mazzilli, S. 93 pp.

Group on Earth Observations. 2005. *Global Earth Observations System of Systems (GEOSS) 10-Year Implementation Plan Reference Document* (final draft).

Hall, J. 2005. *Integrated Marine Biogeochemistry and Ecosystem Research (IMBER) Science Plan and Implementation Strategy*. Interrnational Geosphere-Biosphere Programme, 107 pgs.

Ianson, D. & S. E. Allen. 2002. *Global Biogeochemical Cycles*, 10.1029/2001GB001451.

Jahnke, R., J. Bane, A. Barnard, J. Barth, F. Chavez, H. Dam, E. Dever, P. DiGiacomo, J. Edson, R. Geyer, S. Glenn, K. Johnson, M. Moline, J. O'Donnell, J. Oltman-Shay, O. Persson, O. Schofield, H. Sosik and E. Terrill. 2003. *Coastal Observatory Research Arrays: A Framework for Implementation Planning.* Coastal Ocean Processes (CoOP) Report No. 9, December 2003. Skidaway Institute of Oceanography Technical Report, SkIO TR-03-01, 77 pp.

IOCCG. 1998. *Minimum Requirements for an Operational Ocean-Color Sensor for the Open Ocean*, Reports of the International Ocean Colour Coordinating Group, IOCCG Project Office, Dartmouth, Canada, 46 pp.

IOCCG. 1999. *Status and Plans for Satellite Ocean-Colour Missions: Considerations for Complementary Missions*, Reports of the International Ocean-Colour Coordinating Group, No. 2, J. A. Yoder (ed.), IOCCG, Dartmouth, Canada, 43 pp.

IOCCG. 2000. *Remote Sensing of Ocean Colour in Coastal, and Other Optically-Complex, Waters.* Sathyendrath, S. (ed.), Reports of the International Ocean-Colour Coordinating Group, No. 3, IOCCG, Dartmouth, Canada.

Karl, D. M., J. R. Christian, J. E. Dore, D. V. Hebel, R. M. Letelier, L. M. Tupas and C. D. Winn. 1996. Seasonal and interannual variability in primary production and particle flux at Station ALOHA. *Deep-Sea Research, Part II*, *43*, 539-568.

Kremer, H.H., Le Tissier, M., Burbridge, P., Rabalais, N., Parslow, J., Crossland, C. 2005. *Land-Ocean Interactions in the Coastal Zone (LOICZ) II Science Plan and Implementation Strategy*. Interrnational Geosphere-Biosphere Programme, 72 pgs.

Muller-Karger, F. 2001. SMP Workshop looks at role of continental margins in ocean carbon cycle. *U.S. JGOFS Newsletter*, 10.

NOPP. 2005. *First Annual Integrated Ocean Observing System (IOOS) Development Plan*. The National Office for Integrated and Sustained Ocean Observations Ocean.US Publication No. 9.

Pacala, S. W., G. et al. 2001. Consistent land- and atmosphere-based US carbon sink estimates. *Science*, *292*, 2316-2320.

Sarmiento, J.L. and S.C. Wofsy. 1999. *A U.S. Carbon Cycle Science Plan, Report of the Carbon and Climate Working Group*, prepared for the agencies of the U.S. Global Change Research Program, 69 pp.

UNESCO. 2003. *The Integrated Strategic Design Plan for the Coastal Ocean Observations Module of the Global Ocean Observing System.* GOOS Report No.125; IOC Information Documents Series N°1183.

Walsh, J.J. 1991. Importance of continental margins in the marine biogeochemical cycling of carbon and nitrogen. *Nature*, *350*, 53-55.

Wofsy, S.C. and R.C. Harriss. 2002. *The North American Carbon Program* (NACP). Report of the NACP Committee of the US Carbon Cycle Science Steering Group. Washington, DC: US Global Change Research Program.

Contacts

Janet Campbell (PI)	Research Professor and Director Center for Coastal Observation and Analysis Ocean Process Analysis Laboratory Institute for the Study of Earth, Oceans, and Space University of New Hampshire Durham, NH 03824-3525 USA tel: 603-862-1070; fax: 603-862-0243 email: janet.campbell@unh.edu
Paul DiGiacomo Andrew Bingham Carl Bruce Mary-Elena Carr	Jet Propulsion Laboratory California Institute of Technology MS 301-165, 4800 Oak Grove Drive Pasadena, CA 91109 USA JPL POC email: Paul.M.DiGiacomo@jpl.nasa.gov

COCOA Science Team

Robert Green	AVIRIS Experiment Scientist, Jet Propulsion Laboratory
Robert Arnone	Head Ocean Sciences Branch, Naval Research Laboratory
William Balch	Bigelow Laboratory for Ocean Sciences
Janet Campbell	Research Professor, University New Hampshire
Mary-Elena Carr	Research Scientist, Jet Propulsion Laboratory
Francisco Chavez	Senior Scientist, Monterey Bay Aquarium Research Institute
Paul DiGiacomo	Scientist, Jet Propulsion Laboratory
Mark Dowell	Scientist, CEC Joint Research Centre
Nicolas Gruber	Assistant Professor, Uni. of California, Los Angeles
Chuanmin Hu	Research Professor, Uni. of South Florida
Marlon Lewis	Professor, Dalhousie Uni. and President, Satlantic Inc.
Stephane Maritorena	Research Professor, Uni. of California, Santa Barbara
Curt Mobley	Vice President and Senior Scientist, Sequoia Scientific, Inc.
Mark Moline	Assoc. Professor, California Polytechnic State University
John Ryan,	Project Scientist, Monterey Bay Aquarium Research Instute
Dariusz Stramski	Professor, Scripps Institution of Oceanography, UCSD
Charles Trees	Research Professor, San Diego Sate University
Kirk Waters	Program Officer, NOAA Coastal Services Center