

(4) Ocean Measurements and Models: The Ocean and the North American Carbon Cycle

The oceans play an important role in global uptake of atmospheric CO₂. Of the 4 to 5 Pg C that is annually sequestered into the oceanic and terrestrial reservoirs, approximately half is absorbed by the oceans. Where this uptake occurs, and associated year-to-year variations, are highly uncertain. Regional scale carbon fluxes between the atmosphere and the ocean are the product of a variety of different ecosystem responses to the interactive effects of large-scale climate changes and land-ocean interactions. Large-scale climatic shifts such as the El Niño, the Pacific Decadal Oscillation and the North Atlantic Oscillation cause variability in the regional distributions and fluxes of CO₂ in oceanic waters surrounding the North American continent. Much of the ocean planning effort, however, has been focused primarily on open ocean processes. These programs are likely to be missing a large component of the CO₂ gas exchange along the ocean margins. These near-shore fluxes can affect the CO₂ composition of the air masses impacting the North American continent. Coastal upwelling and biological production rates are high in these regions and the continental margins receive large carbon fluxes from rivers. In addition, a large fraction of the ocean's surface waters may acquire their chemical and biological characteristics that control net CO₂ exchange while in margin systems and/or via margin processes. The role of the margins in controlling the partitioning of CO₂ between the atmosphere and the oceans is very likely much larger than can be sustained by air-sea exchange within the geographic boundaries of margins. The North American Carbon Program will therefore clearly require a program focused on understanding the role of coastal systems have in affecting atmospheric CO₂ distributions.

Continental margins are the active interface between terrestrial and marine environments. They are regions of active physical and biogeochemical processes capable of transforming, transporting or burying huge amounts of carbon, and affecting atmospheric CO₂. The coastal ocean can respond quite differently than the open ocean to climatic perturbations. For example, sea-surface temperature increases in the open ocean, due to seasonal heating and/or ENSO events, can lead to higher surface water pCO₂ values and higher amounts of CO₂ evasion. However, ENSO events can also lead to sharp decreases in coastal upwelling and reduced levels of CO₂ outgassing in near-shore regions. Meteorological and longer-term (climate, land use) influences on runoff have dramatic impacts on nutrient inputs and the export flux of carbon in coastal margins. Runoff rate changes resulting from ENSO events may also change the partitioning of material discharged to the ocean, and impact individual component fluxes of DOC, POC, and DIC to the ocean. Ocean margins receive substantial terrestrial carbon inputs; have large carbon burial rates and rapid carbon turnover times, yet their role in the ocean's carbon cycle is not well understood. Continental margins, because of the sensitivity of their circulation and biological production to changes in winds, river runoff and anthropogenic inputs of nutrients, are regions

likely to be sensitive to climate change. Episodic and seasonal nutrient injections, through upwelling and riverine input, support high rates of primary productivity that contribute significantly to carbon export from surface waters, across the continental shelf and into the deep ocean. At the same time the upwelling of deep cold water, enriched in CO₂ as a result of the respiration of settling particles, may represent a localized source of atmospheric CO₂. Even if the annual net air-sea CO₂ flux, resulting from deep-water ventilation and biological productivity, may be close to zero, the spatial and temporal decoupling of these two processes can produce transient gradients in atmospheric CO₂ in the atmospheric boundary layer of coastal regions.

Specific objectives of new ocean margins studies are better estimates of air-sea fluxes of CO₂ and carbon burial and export to the open ocean, elucidation of factors controlling the efficiency of the solubility and biological pumps in coastal environments, quantification of the influence of margin biogeochemical processes on the chemical composition of open ocean surface waters that may control open ocean CO₂ exchange, and the development of coupled physical-biogeochemical models for different types of continental margins.

Biogeochemical processes in margins that are likely to be sensitive to climate change and quantitatively important to basin-scale carbon cycling include terrestrial carbon inputs, calcification/dissolution, sediment/water column exchanges, production and sequestration of POC and PIC, denitrification and cross-shelf transport/transformation of POC and DOC. Areas of particular concern due to their dominant role in coastal carbon budgets are river-dominated margins and coastal upwelling regions. The coarsely gridded global pCO₂ dataset used in a recent assessment of the air-to-sea CO₂ flux (Takahashi et al., 2001) was not designed to accommodate ocean margins and therefore did not include contributions from coastal areas. There is growing evidence that climate variability is accentuated in the coastal regions off North America. For example, in the upwelling regions off the west coast of North America fluctuations of the air-sea-exchange of CO₂ can exceed 50 moles m⁻² yr⁻¹ on short time scales. The atmospheric component of the NACP involves enhancement of the long-term sampling network to include coastal environments. These aircraft profiles and tall tower measurements have footprints (~1000 km) that would extend well into the ocean margins. A coordinated ocean observations program is necessary to interpret the atmospheric signals that will be obtained with this program.

Recent efforts by the Continental Margins Task Group within the International JGOFS Program have demonstrated that river-dominated margins such as in the East China Sea may serve as large CO₂ sinks by exporting a significant fraction of river-discharged and locally produced organic carbon to the open ocean. It is still not clear, however, whether the continental shelf regions around North America are a net sink or a net source of CO₂ to the atmosphere. The terrestrial component of the NACP will examine regional to continental-scale carbon fluxes. Significant fluxes are associated with transport within groundwater and rivers to

the coastal ocean. A coordinated ocean observation program will help to constrain carbon losses from the terrestrial system to the oceans.

The oceans component of the NACP is designed to leverage existing programs to better constrain the role of the oceanic regions bordering North America, and to define the net effect of the marine system on the CO₂ of the air exchanging with the continental air masses. The main objective of the ocean research component will be to provide information on processes controlling seasonal and interannual air-sea CO₂ fluxes within the open-ocean and ocean margins regions surrounding North America. A quantification of these processes is necessary to understand and interpret the large-scale regional and continental CO₂ flux estimates that will be obtained during the intensive field experiment in 2004-2005. Plans being developed to address the global issues, such as the U.S. Large Scale CO₂ Observation Plan [Bender et al., 2001], have significant ocean components that complement the NACP, making close coordination between these programs and the NACP vital.

Developing Ocean Carbon Initiatives

Recently several NSF, NOAA and NASA-sponsored workshops have engaged in an effort to identify specific research objectives that would improve our understanding of carbon dynamics in the ocean. Strikingly, several themes were common among federal agencies. These include:

- What are the critical components of the ocean carbon cycle regulating the partitioning of CO₂ between the atmosphere and the ocean on seasonal to interannual timescales, and how can we improve prediction of the response of these processes to changes in environmental conditions (e.g., due to global warming)?
- How do we adequately characterize the non-steady state behavior of oceanic systems?
- How do components of the ocean system - physical and ecological – move between semi-stable states?
- What are the stabilizing (negative) and destabilizing (positive) feedbacks inherent in the system?
- How can biological, physical and chemical processes be more realistically represented in ocean carbon cycle models?
- What are the potential responses of marine ecosystems and ocean biogeochemical cycles to climate?

Implementation of any research effort that addresses ocean carbon cycling in a global context will require an integrated earth systems approach that incorporates various disciplines and interagency partners. Below are brief descriptions of the interagency planning efforts for ocean carbon program that directly address the scientific questions of the North American Carbon Cycle Field Experiment.

NOAA GCC - The NOAA Global Carbon Cycle (GCC) Program will focus its efforts on the large-scale distributions and fluxes of CO₂ in the coastal and open ocean regions of the North Atlantic and North Pacific Oceans. The NOAA GCC program envisions a major expansion of sea surface CO₂ measurements and related properties in the North Atlantic and the North Pacific (including the Equatorial Pacific). The measurements will be made primarily using 8-12 volunteer observing ships (VOS), supplemented by time-series measurements. The North Atlantic and North Pacific studies will provide constraints for improved inverse model estimates of the North American carbon sink, will yield robust values of air-sea CO₂ fluxes in the coastal and open ocean regions on both sides of North America, and will give important and extensive new information about biogeochemical processes.

NSF CoOP - The NSF CoOP (Coastal Ocean Processes) Program is currently sponsoring research on the transport and controlling biogeochemical processes at a variety of US margin environments. The CoOP research plan is to conduct process and modeling studies on shelves that differ in the dominant physical processes which influence cross margin transport and control biogeochemical characteristics. CoOP studies thus attempt to isolate key processes that have some global generality and to study these in detail on margins where effects can be isolated with a maximum degree of confidence. Modeling studies are integrated with the process studies and used to synthesize and generalize study results. CoOP presently supports research programs along margins characterized by wind-induced transport on the coasts of California and Oregon.

NSF RiOMar - As a component of NSF's global carbon cycle research efforts, the RiOMar (River-dominated Ocean Margins) initiative focuses on process studies of carbon transformations and transport in continental margins impacted by major river inputs (such as the Mississippi River system in North America). The decadal-scale storage of terrestrial carbon within the terrestrial portions of some river systems may be much more important than previously recognized. Recent findings suggest that the ages of DOC and POC being discharged from rivers are generally older and more variable (i.e., across different river systems) than previously believed. RiOMar systems are important global sites for burial of organic carbon and other biogeochemically important materials. Globally ~ 90% of modern organic carbon burial occurs in RiOMar systems (deltas and associated shelf environments). Despite the prominence of sediment burial, large quantities of organic carbon are remineralized in RiOMar environments, as a result of diagenetic transformations and subsequent transport in dissolved or

colloidal forms. Annually, the total organic carbon burial in marine sediments is equivalent to less than one-third of the riverine organic carbon discharge--- indicating that riverine organic matter is rapidly mineralized or preferentially transported off the margin.

NASA CCI - The NASA Climate Change (CCI) Initiative will support observational programs of carbon cycling and air-sea fluxes in selected coastal and open-ocean regions surrounding the continental United States and Alaska. The program will focus on the quantification of air-sea CO₂ fluxes, carbon transport (including downward export out of the mixed layer), and biogeochemical transformations of carbon (e.g., photochemistry of DOC). The existing suite of satellite observed ocean parameters includes surface winds (scatterometry and passive microwave radiometry), ocean circulation (altimetry), sea surface temperature (SST; infrared radiometry), and chlorophyll-a concentrations (ocean color) and primary production (ocean color with additional ancillary information on SST, mixed layer depth, surface irradiance, etc.). Future algorithm development efforts will focus on additional carbon products such as dissolved organic carbon, particulate organic carbon, new production, export production, phytoplankton functional groups (e.g., coccolithophores, trichodesium) and air-sea CO₂ fluxes using remote sensing inputs. NASA currently has an airborne combination pulse-probe lidar/hyperspectral radiometer for phytoplankton and ocean carbon studies and an airborne microwave radiometer for ocean salinity measurements both of which would be extremely useful for the coastal studies envisioned under the NACP. A satellite salinity mission has been proposed to the most recent Earth System Sciences Pathfinder program, but the evaluations have not been released as yet. NASA is also developing a lidar system for profiling particle concentrations from a ship or aircraft. The ocean component of the NASA CCI will provide in situ, aircraft, and satellite measurements for a variety of important marine parameters. Appendix 1 provides a summary of the relevant satellite and aircraft observations that are available, under development, approved, or recommended over the next decade. To better utilize remote sensing data for understand the underlying physical, biological, and chemical processes, NASA will invest in the development of refined ocean carbon cycle process and ecosystem models capable of integrating remote sensing and in situ measurements. The refinement of these models will require additional field measurements as indicated above. Related modeling activities are already underway as part of the NASA Seasonal-to-Interannual Prediction Program (NSIPP), which is developing methodologies for assimilating physical oceanographic data into global scale coupled ocean-atmosphere numerical models. The model development activity will integrate biological/chemical/physical modeling on several scales, including detailed process models, local and regional site-specific models, diagnostic, inverse and data assimilation models, and global ocean biogeochemical models.

Close coordination of the interagency field and modeling programs on controls of carbon cycling in the North Atlantic and North Pacific Oceans will provide a

worthwhile contribution to the North American Carbon Program. Through the CCSP Interagency Working Group, the three federal agencies will maintain and expand data management efforts to provide both active project data management, timely submission of data through a formal data policy, access to existing and emerging data, and long term archiving. They will improve and expand distributed, online access to biogeochemical data sets and synthesis products worldwide.

The Role of Ocean Carbon within the NACP

All of the programs mentioned above can contribute to the success of the NACP. The ocean carbon component of this program will be to coordinate the efforts of these various components into a complimentary integrated observing system. This system can be broken down into two components: The open ocean domain and the coastal ocean domain (Fig. 1).

Open Ocean Domain

Characterization of the air-sea fluxes in oceanic regions bordering North America is critical for isolating processes related to the study region. The long-term basin-scale observation network of underway and time-series measurements laid out in the U.S. Large-Scale CO₂ Observations Plan (Bender et al., 2001) will provide the measurements necessary to constrain the boundary conditions for the NACP. A description and justification of the large-scale sampling program is given by Bender et al. (2001) and is not repeated here.

One of the objectives of the LSCOP is to better characterize the spatial and temporal variability of air-sea fluxes in the North Pacific and North Atlantic. Currently we have a reasonably good understanding of the global scale sources and sinks of CO₂ in the oceans based on the sea-surface pCO₂ climatology developed by Takahashi and coworkers [1999]. However, there is still very little information on temporal variations of CO₂ sources and sinks. The open ocean measurements will improve this constraint for the NACP and also help place the NACP results into more of a global context by monitoring changes in air-sea CO₂ gradients in the remote North Pacific and North Atlantic that correlate with observed seasonal and interannual changes in the net North American uptake.

Coastal Ocean Domain

Continental margins are the active interface between terrestrial and marine environments. Ocean margins receive substantial terrestrial carbon inputs; have large carbon burial rates and rapid carbon turnover times, yet their role in the ocean's carbon cycle is not well understood. Continental margins, because of the sensitivity of their circulation and biological production to changes in winds, river runoff and anthropogenic inputs of nutrients, are regions likely to be sensitive to climate change. Specific objectives of new ocean margins studies are better

estimates of air-sea fluxes of CO₂ and carbon burial and export to the open ocean, elucidation of factors controlling the efficiency of the solubility and biological pumps in coastal environments, quantification of the influence of margin biogeochemical processes on the chemical composition of open ocean surface waters, and the development of coupled physical-biogeochemical models for different types of continental margins. Biogeochemical processes in margins that are likely to be sensitive to climate change and quantitatively important to basin-scale carbon cycling include terrestrial carbon inputs, calcification, sediment/water column exchanges, and cross-shelf transport/transformation of POC and DOC. Areas of particular concern due to their dominant role in coastal carbon budgets are river-dominated margins and coastal upwelling regions (Fig. 1).

Leveraging off the NSF and NASA coastal programs, the NACP can directly evaluate the role that coastal regions play in the North American carbon cycle. Through the NACP, shelf and estuarine studies can be directly tied to atmospheric and terrestrial signals. The coastal program will include (1) long-term observations using coastal transects and buoys with autonomous sensors, and (2) intensive process studies. The long-term observations will be coordinated with aircraft profiles and coastal terrestrial study sites to provide the most complete picture possible at these sites. The long-term sites will also be coordinated with the anticipated location of the process studies to better characterize the dominant controls on the observed CO₂ signals.

Ocean Carbon Modeling

Tracking changes in organic and inorganic carbon pools in the coastal ocean and open-ocean regions involves a better understanding of ecosystem dynamics, interlinking biogeochemical cycles, and oceanic physical circulation. Accurate determination of air-sea CO₂ fluxes requires an understanding of processes including upwelling, primary production, physical and biological transport, remineralization, sedimentation, etc., and are likely to undergo broad changes under variable climate conditions. The NACP modeling effort will be designed to assimilate process study information and estimate regional sources and sinks for carbon. Integration of such a wealth of information will be a formidable task, but it is envisioned that developing a cohesive ocean carbon program within the framework of the CCSP will act as a first step in such an effort.

Quantification of coastal and open-ocean carbon fluxes will involve a hierarchical approach, with a widely distributed, representative set of observations and modeling efforts. The field experiments will provide a foundation for satellite and model-based interpolations of oceanic CO₂ fluxes over a broad range of temporal and spatial scales. The modeling program will be designed to assimilate field results and determine regional CO₂ sources and sinks. The North American Carbon Cycle Field Experiment requires these estimates of oceanic CO₂ fluxes in order to constrain the continental flux estimates. This experiment also would

provide a unique opportunity to coordinate the planned Global Carbon Cycle Research efforts of several federal agencies focusing on carbon cycling in the coastal margins of the United States.

Appendix X. Initial concepts for the ocean observations

The ocean observation component of the NACP is focused on addressing two basic issues. How much carbon is sequestered by the open ocean? How do the coastal oceans impact atmospheric CO₂ values associated with the North American continent? The division between the open and coastal oceans is somewhat artificial, but is operationally defined as the boundary between the highly variable surface waters near the coast and the relatively stable off-shore waters. The physical location of this boundary varies depending on region, but the size of the coastal footprint can vary from 50 to 500 km from shore depending on environmental conditions. (Fig. 2). The development of the open-ocean and coastal observation networks outlined below is expected to grow over the next few years in coordination with the ring of coastal atmospheric stations. These programs will hopefully continue on beyond the initial intensive portion of the NACP to provide information on interannual variability. The intensive work proposed in the Coastal Network section is scheduled to occur in the 2004-2006 time frame to coincide with field programs proposed by NASA and NSF.

Open-Ocean Network

The North Atlantic and North Pacific studies will information on the boundary conditions for the NACP. It will also help put the NACP into a larger scale context, and will provide constraints for improved inverse model estimates of the North American carbon sink. The NACP will leverage currently planned and existing open-ocean programs that focus on large-scale distributions and fluxes of CO₂ [see Bender et al., 2001]. The primary component of this program will be surface seawater and atmospheric CO₂ measurements made using automated shipboard instruments. The measurements will be made using 8-12 volunteer observing ships (VOS) that transit the North Pacific and North Atlantic along repeated ship tracks at monthly to seasonal intervals. Example lines might include tracks between Seattle, WA and Tokyo, Japan; Los Angeles, CA and Hong Kong; Southampton, England and Panama; Lisbon, Portugal and New York, NY. The transects will be designed to cover the range of oceanographic regions. Time-series stations located at key locations in the North Atlantic and North Pacific will provide additional information on higher frequency variability. Various process studies and large-scale survey programs being developed for the North Atlantic and North Pacific will also contribute to a better understanding of the open-ocean carbon cycle. These data will yield robust values of air-sea CO₂ fluxes in open-ocean regions on both sides of North America, and will provide strong boundary constraints for improved inverse model estimates of the North American carbon sink.

Coastal Ocean Network

The coastal ocean program is envisioned as a set of meridional and zonal VOS ship transects and time series stations, focusing on high-resolution observations of the air-sea fluxes of CO₂ in the continental margins of North America (Fig. 1). The time-series moorings will make high-resolution measurements in the surface water and atmosphere. Monthly to seasonal transects past the time-series moorings, perpendicular to the coast will characterize the on-shore-off-shore gradients on monthly to seasonal time-frames. These transects, together with large-scale, seasonal, along shore survey cruises will help place the time-series moorings in a spatial context. Measurements would include basic meteorological and hydrographic data, atmospheric and oceanic pCO₂, organic carbon, nutrients and primary production. These data can be used to determine net oceanic CO₂ fluxes. These observational networks would be coordinated with aircraft surveys to obtain large-scale vertical and horizontal distributions of pCO₂ in the troposphere. The observational program will also include a limited number (5 or 6) intensively studied sites in representative ecosystems including: the Mid Atlantic Bight from Cape Cod to Cape Hatteras; the South Atlantic Bight; the West Coast region; the Gulf of Maine; the Mississippi Delta region and the Bering Sea. These sites will be centered at the time-series moorings to better understand the controls on the observed CO₂ variability and the net magnitude of the sink/source of that region.

Long-term studies by programs like RiOMar will provide valuable information on land-ocean interactions and transformations. NACP will provide a forum for the coastal oceanography and terrestrial scientists to coordinate efforts and better ensure that no major source or sink regions in the wetland and coastal environments are missed. Both the near-shore terrestrial and ocean scientists will work with atmospheric scientists to interpret signals observed in coastal towers and aircraft profiles.

Coordination with Satellite Observations

It is a goal of the NASA CCI to integrate the field observations required for algorithm development (bio-optical and atmospheric correction), satellite calibration and product validation, and model process parameterization and formulation to the greatest degree possible in order to ensure complete data sets. The field measurements will include inherent and apparent ocean optical properties, biological properties (species, pigments, photosynthetic rates, etc.), and chemical and hydrographic properties (salinity, nutrients, dissolved and particulate carbon concentrations, etc.). In most cases, these field experiments will be joint cruises with NOAA and NSF. The NASA strategy will be to augment open-ocean sampling on NOAA and NSF cruises in the North Atlantic and North Pacific and at the Bermuda and Hawaii time-series sites. For the more complex coastal studies, a detailed interagency strategy will be developed to account for the use of smaller vessels (fewer investigators, hydrographic winches, wet lab

space, etc.) and differing data collection strategies (time series, survey, process studies, algorithm development, etc.). Algorithm development and process parameterization studies will require at least seasonal cruises in a variety of sites to capture the variability needed for these formulations. Suggested coastal sites for bio-optical algorithm development are the same regions suggested for the intensive studies. The acquisition of observations will be coordinated for each cruise so as to minimize redundancy, maintain data consistency and quality, and maximize data use. Finally, an interagency strategy for data submission, quality assurance, and management is being developed. One example of an existing data management arrangement is a collaboration between the NASA Sensor Intercomparison and Merger for Interdisciplinary Oceanic Studies (SIMBIOS) project and NOAA's National Oceanographic Data Center (NODC) where bio-optical data collected by NASA-supported investigators for ocean color algorithm development and product validation is provided to NODC for general distribution.

Appendix: 1. Satellite Remote Sensing Contributions to the NACP

As discussed in the main text, there are a number of historical, on-orbit, approved, and proposed satellite missions that can contribute to the goals, both near term and long term, of the NACP. Table 1 provides a brief compilation of the instruments as they apply to the various processes associated with major land-ocean-atmosphere carbon flux categories, i.e., air-sea CO₂ and carbon export (to the deep ocean), land-atmosphere CO₂, land-atmosphere CH₄, and land-sea carbon fluxes. In many cases, if not most, derivation of the specific carbon-related parameters sought from these data sets will need considerable investment in algorithm development and validation. The field experiments conducted under the NACP would offer opportunities for these purposes, but additional independent NASA-sponsored experiments will probably be required in order to obtain data sets of sufficient diversity and completeness. Note that Table X.X is not a comprehensive list of all land, ocean, and atmospheric earth observing missions and data sets that might be considered, but are those deemed to be the most critical to the NACP. Also, missions in the time frame of the NACP that are important for aerosol radiation forcing evaluations are listed because they may be of indirect use in some carbon budget analyses. The NASA technology development program provides a progression of opportunities from the component level to demonstration missions. Table X.X entries include contributions from the Instrument Incubator Program (IIP), the New Millennium program, and the Earth System Sciences Pathfinder (ESSP). The IIP produces prototype instruments which may be deployed on aircraft. New Millennium missions, e.g., EO-1 Hyperion (a passive hyperspectral imager), are satellite demonstrations with limited data acquisition and processing. The ESSP emphasizes a more comprehensive satellite observational and data processing requirement, but with a limited duration (1-2 years), e.g., the Vegetation Canopy Lidar (VCL). During the summer of 2001, the IIP and ESSP completed selections. IIP instruments that should be ready for the initial NACP field campaigns include passive and laser CO₂ airborne systems. The ESSP

selections have not been announced and are subject to additional down-selections before final approval, so it is unclear at this time what the future ESSP contributions to the NACP will be. Under the 2001 NASA initiative for climate change research, several carbon-related observations have been identified including:

- Atmospheric CO2 concentration;
- Stocks and rates of change in terrestrial biomass;
- Oceanic primary productivity and dissolved organic carbon;
- Air-sea CO2 fluxes;
- Atmospheric aerosol absorption and scattering properties and cloud microphysics.

While the existing/scheduled instruments in Table X.X can contribute to these measurement needs, few are optimized for these purposes which is why new missions are desired. Unless some of these observational needs are met under the most recent ESSP selection process, spaceborne observations of these quantities will be limited during the early phases of the NACP.

The NASA initiative includes field studies aimed at improving model parameterizations of key carbon cycle processes with satellite data assimilation for enhancing model accuracy and earth system predictability. Wherever possible, field data collection for process model development, remote sensing algorithm development, and product validation will be integrated. This framework of observations and modeling parallels that of the NACP and was designed with the NACP in mind as a first step towards developing a global capability in collaboration with other U.S. and international agencies.

TABLE 1: PRIMARY A/C & SATELLITE CONTRIBUTIONS TO THE NACP

Required	Approved Programs		Recommended New Measurements
	Historic	EOS Era	
Land-atmosphere CO2 flux ProductivityLand			Thru 2010 Atmospheric CO2 variabilityLand

Cover TypeDisturbance/Recovery Biomass AVHRR, SeaWiFSAVHRR Landsat
MODIS

HyperionSeaWiFSAVHRR Landsat Landsat ESSP: TBDIIP: FPI(GSFC) &
LIDAR

(JPL)VIIRSLandsat DataContinuityMissionVCL CO2 Sounders &

LidarsBiomass Mission

Land-atmosphere CH4 flux Atmospheric CH4 TES

Air-sea CO2 flux and carbon export Wind speedSea Surface

Temp.SalinityChlorophyllProductivityOrganic Carbon(Particulate

&Dissolved)Inorganic CarbonConcentrationCirculation and hydrography

AVHRRSeaWiFSTOPEX QuikscatSeaWindsAVHRRSeaWiFS
MODISGLIMERISMODISGLIA/C

Laser - Hyperspectral RadiometerGLIJason Follow-onmissionsVIIRSESSP:

TBDVIIRSA/C Particulate Lidar Ocean C MissionOcean C MissionOcean C

Mission

Aerosols AVHRR,TOMSSAGE IISCIAMACHY MODISMISR,
OMISAGE III VIIRSESSP:

TBDPARASOL Polarimeter

Acronyms:

AVHRR Advanced Very High Resolution Radiometer

ESSP Earth System Sciences Pathfinder

FPI Fabry-Perot Interferometer

GLI Global Imager

IIP Instrument Incubator Program

MERIS	Medium-Resolution Imaging Spectrometer
MISR	Multi-angle Imaging Spectrometer
MODIS	Moderate-Resolution Imaging Spectroradiometer
OMI	Ozone Monitoring Instrument
PARASOL	Polarization and Anisotropy of Reflectances for Atmospheric Science coupled with Observations from a LIDAR
SAGE	Stratospheric Aerosol and Gas Experiment
SCIAMACHY	Scanning Imaging Absorption Spectrometer for Atmospheric Cartography
SeaWiFS	Sea-viewing Wide Field-of-view Sensor
TES	Tropospheric Emission Spectrometer
TOMS	Total Ozone Mapping Spectrometer
TOPEX	Ocean Topography Experiment
VCL	Vegetation Canopy Lidar
VIIRS	Visible and Infrared Imaging Radiometer Suite