Ocean Ecosystems

Introduction

The Earth's ecosystems are comprised of a myriad of physical, chemical, biological and ecological processes that create a variety of adaptive and resilient communities of organisms on both the land and in the sea. These ecosystems are an integral part of the planet's biogeochemical cycles (e.g., carbon, nitrogen, phosphorous, silica, iron, etc.), which, in turn, are coupled to and influence the planet's climate through feedback processes, many of which are not clearly understood. With the advent of satellite ocean color technology, the global distribution of marine biosphere properties such as chlorophyll concentration, water clarity, primary production, particle concentrations, and others can be routinely surveyed and monitored over time. The data have been used, along with other biological and hydrographic data, to identify ocean biogeochemical provinces and to define the ecological geography of the ocean (Longhurst, 1998). These capabilities, along with improved measurements at sea and numerical models of ocean circulation and ecosystem dynamics, are revolutionizing our understanding of the marine biosphere and how it interacts with the rest of the Earth system. The ACE ocean science objectives represent a major advance in ocean ecosystem and biogeochemical research and require a huge step forward from traditional satellite ocean color measurement capabilities. In this chapter, the science objectives and rationale are outlined as are the commensurate measurement requirements.

The Carbon Cycle

In outlining the ACE mission, the Decadal Survey highlighted the need for continued measurement of marine primary production to refine estimates of the air-sea exchange of CO_2 and its long-term CO_2 sequestration in the deep ocean. Implicit in this requirement is the need to understand how marine ecosystems are changing and the corresponding temporal changes in the distribution and composition of phytoplankton and the processes that are regulating these. Figure 1 depicts the global carbon cycle with current estimates of the terrestrial, oceanic, and atmospheric reservoirs and fluxes. The deep ocean is, by far, the largest reservoir of carbon readily available to the "active" component of the carbon cycle. Of course, there are larger reservoirs in sedimentary rock formations and other geological deposits, but these are essentially unavailable except via the extraction and use of fossil fuels as shown in Figure 1. The net uptake of carbon by both the terrestrial and oceanic systems is relatively small representing the difference between much larger fluxes. Estimates of biological CO_2 incorporation through net primary production are similar (~50 GtC/yr) for global terrestrial and ocean systems, and are

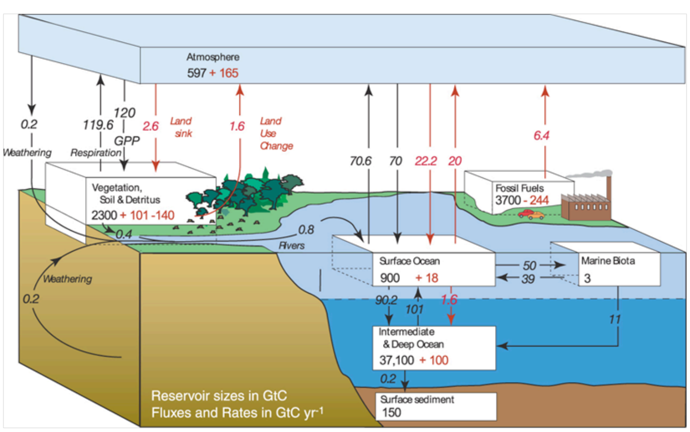

Figure 1. Global carbon cycle

approximately matched by concurrent respiratory CO_2 production and export to the deep sea. The anthropogenic CO_2 source is 6.4 GtC/yr, with roughly half of this annual flux sequestered by ocean and terrestrial systems. Ocean uptake is mediated through exchange with the overlying atmosphere, so as atmospheric CO_2 concentrations rise, the ocean concentration adjusts accordingly; but ocean uptake is tied to the ocean's bicarbonate system. Ocean biology modulates the bicarbonate system primarily through the uptake of CO_2 by photosynthesis. The surface equilibrium is disrupted by exchanges of carbon with the deep ocean. These exchanges (Figure 2) are driven by ocean circulation (water mass subduction and convection) and the sinking particle fluxes (the so-called "biological pump"). As Figure 2 implies, the carbon pathways and transformations in the ocean are complex and depth dependent. Satellite observations are critical for measuring bio-optical and chemical properties near the surface and models are essential to understanding how ocean ecological processes ultimately modulate the air-sea fluxes and the exchanges with the deep ocean leading to the long-term sequestration of fossil fuel CO_2. Achieving an accurate quantification of the distribution, composition, and vertical fluxes of particles is a key objective of the ACE mission.

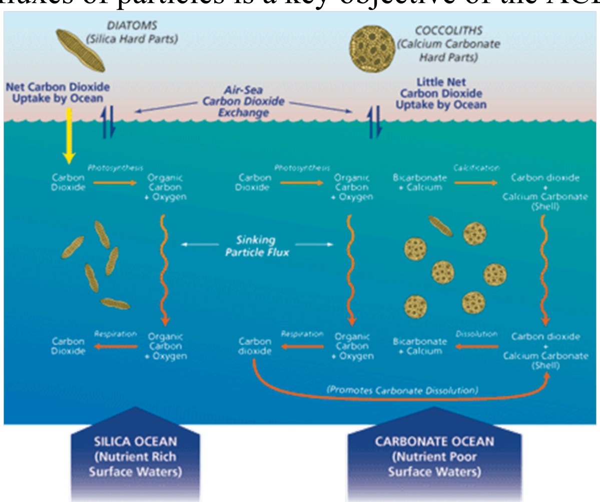

Figure 2. Ocean carbon cycle processes

The historical approach for quantifying ocean primary production was to develop algorithms based on chlorophyll concentrations, such as that introduced by Behrenfeld and Falkowski (1997). Their algorithm also incorporated sea surface temperature (SST) and photosynthetically-available radiation (PAR), both of which are available with high accuracy from satellite observations. A problem with deriving chlorophyll concentrations using ocean color is that other in-water constituents also absorb blue light, particularly colored dissolved organic matter (CDOM), and are ubiquitous in the surface ocean (Siegel et al, 2005). The chlorophyll-a absorption peak is at 443 nm, but CDOM absorption continues to increase at shorter wavelengths. The CZCS did not have any bands in the near-UV which would have allowed for the separation of these pigments. SeaWiFS, MODIS, and other "second generation" sensors have incorporated a band at 412 nm that allows the retrieval of CDOM (see Siegel et al. 2005). The impact of this uncertainty is illustrated in Figure 3, which compares primary production estimates using the standard NASA chlorophyll algorithm (which does not account for spatio-temporal variability in CDOM) and chlorophyll derived from a reflectance inversion algorithm (Maritorena, et al., 2002) that resolves CDOM variability. The difference in global annual production for these two chlorophyll estimates is roughly 16 GtC/yr, **representing an uncertainty in annual ocean productivity of ~30%!** *Constraining this uncertainty requires extension of measurement bands into the near-ultraviolet (to reduce uncertainties in CDOM retrievals) and improved spectral resolution in the visible band to improve quantification of phytoplankton pigment absorption.*

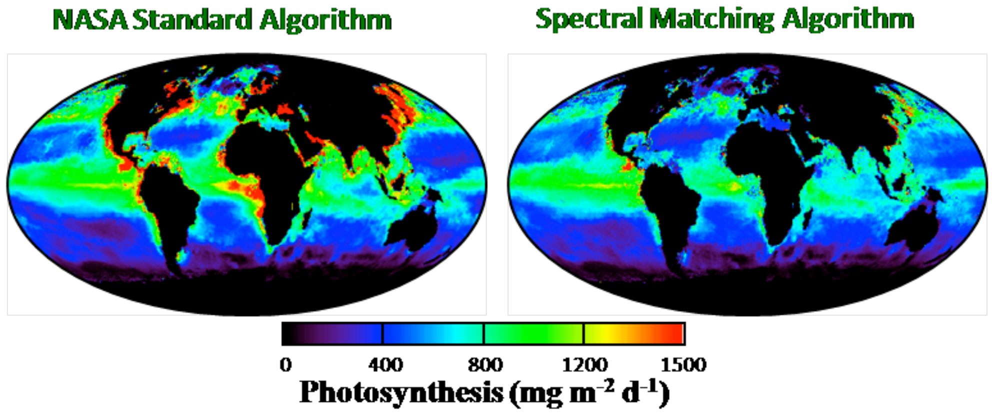

Figure 3. Net primary production as computed using chlorophyll-a derived from two different algorithms, the NASA empirical radiance ratio algorithm and a reflectance inversion algorithm (also called spectral matching).

In addition to the challenge of accurately retrieving surface phytoplankton pigment concentrations, current NPP algorithms do not accurately account for phytoplankton physiological variability. Specifically, the concentration of phytoplankton pigments is a function of both the standing stock of phytoplankton (biomass) and their physiological state (which impacts intracellular pigment levels). **Without distinguishing these two sources of variability, accurate estimates of NPP cannot be made and consequently, neither can accurate estimates of change over time**. For example, if a decrease in surface chlorophyll is observed with increasing surface temperature (as found over the SeaWiFS record), the change could be associated with a decrease in NPP from decreasing stocks or growth rates or it could be associated with improved upper ocean light conditions (photoacclimation) that is may be paralleled by no change or even an increase in NPP. One more recent approach for addressing these issues in remote sensing data was described by Behrenfeld et al. (2005) and Westberry et al. (2008). In their approach, coincident remote sensing retrievals of particulate backscattering coefficients and pigment absorption were used to quantify phytoplankton carbon (C) biomass and physiological state (through Chl:C ratios). While representing a significant conceptual step forward, this new approach remains compromised by inadequacies in current remote sensing and field measurement capacities. In particular, relationships between particle backscattering and phytoplankton biomass are dependent on the composition and particle size distribution of plankton ecosystems. Also, relationships between Chl:C and phytoplankton growth rates are sensitive to variations in the relative concentration of auxiliary photosynthetically active pigments. Furthermore, direct field measurements of phytoplankton C concentrations for product validation are extremely difficult and time consuming and thus are rare in historical databases. Consequently our understanding of Chl:C and its relationships with growth rate and photoacclimation are largely limited to results from laboratory experimentation. *To address these serious issues, significant expansion of the UV-VIS spectral range and resolution of remote sensing measurements are required to adequately improve estimates of particle size distributions and phytoplankton pigment absorption. To support these expanded remote sensing requirements, a significant and parallel effort is needed to establish field data sets of* *appropriate system properties (e.g., phytoplankton C, absorption:C ratios, growth rate, acclimation irradiance) for product validation*.

The aforementioned developments (consistent with the ACE mission design) will make major contributions toward constraining ocean productivity assessments and the accurate interpretation of observed change, but represent only a portion of the ocean carbon system. A more complete understanding of carbon budgets requires estimates not only of carbon fixation rates but of standing stocks of carbon as well, including particulate organic carbon (POC), particulate inorganic carbon (PIC), dissolved organic carbon (DOC), and dissolved inorganic carbon (DIC). To this end, advances have already been made in developing algorithms for POC (Gardner et al., 2006 and Stramski et al., 2008), PIC (Gordon et al., 2001, Balch et al., 2005), and calcification rate (Balch et al., 2007) from remote sensing. Applying one such algorithm to current remote sensing data, for example, Balch et al. (2005) estimated the standing stocks of particulate inorganic carbon (PIC, primarily calcite) and particulate organic carbon to be 19 Mtons and 665 Mtons, respectively. Balch et al. (2007) further estimated the annual mean calcification rate to be 1.6 GtC/yr, which is small compared to the primary production rate, yet important for understanding changes due to ocean acidification. However, the efficiency of export of POC to PIC to the deep ocean must be factored in when considering the relative contribution to deep ocean carbon sequestration. The global determination of DOC remains elusive as DOC concentrations are not simply related to CDOM (Siegel et al. 2002; Nelson et al. 2010). However regional algorithms for estimating DOC for coastal regions influenced by terrestrial inputs have been successful (e.g., Del Castillo and Miller (2008) and Mannino et al., (2008)). Given that DOC is the largest ocean organic carbon pool, tracking the global surface concentration distribution would be a significant achievement. DIC has no optical signature and its concentrations must be modeled by knowing the fluxes in and out of the DOC pool. Estimates of air-sea CO_2 flux require ocean pCO_2 values and an algorithm for the gas transfer function. Signorini and McClain (2009) examined the global fluxes using the latest pCO_2 climatology (Takahashi et al., 2009) with various combinations of wind products and gas transfer functions. The range of net flux values was 0.9-1.3 GtC/yr into the ocean which is somewhat less that that depicted in Figure 1. The expanded capabilities of the ACE ocean radiometer will result in refined estimates of surface carbon pools(e.g., PIC, POC) and rates (e.g., NPP) which can be assimilated into global models to constrain the model estimates of carbon cycling in the water column and improve estimates of surface CO_2 fluxes and carbon export to the deep ocean.

Marine Ecosystems

The world's oceans represent a mosaic of unique biomes and biogeochemiscal provinces. Longhurst (1998) identified 56 pelagic provinces based on an examination of the seasonal cycles of phytoplankton production and zooplankton consumption. While species composition can be diverse often a specific phytoplankton species or functional type dominates. There are different ways of delineating these, e.g., size class (picoplankton, nanoplankton, etc.) and functional groups (diatoms, coccolithophores, *Trichodesmium*, cyanobacteria, etc.). For instance in the subpolar North Atlantic, production early in the year is due primarily to diatoms, but later in the summer, coccolithophores become abundant, preferring more stratified conditions. Thus, depending on the physical environment, availability of macro- and micro-nutrients, illumination, and the concentration of grazers, phytoplankton populations vary in their biomass, species composition, photosynthetic efficiency, etc. These variations regulate primary production and, therefore, higher trophic levels within the ecosystem, and play an important role in the cycling of macro- and micro-nutrient concentrations. Identifying these distributions and properties and how they change on seasonal and interannual time scales is key to understanding how ecosystems function and how they respond to changes in the physical environment, whether natural or human-induced.

Until recently, research on optical identification of specific species has focused on coccolithophores and *Trichodesmium* because of their rather unique spectral reflectance signatures. Coccolithophores are made of calcite platelets and can be identified in satellite data because, at high concentrations, the reflectance is uniformly elevated across the spectrum. Global coccolithophore distributions were first assessed using CZCS data (Brown and Yoder, 1994). As discussed above, calcite can now be estimated from satellites and serves as an indicator of coccolithophore populations. However it is not an accurate indicator of viable coccolithophore cell cencentrations because much of the calcite is in the form of detached platelets. Coccolithophores prefer stratified conditions and are susceptible to acidification. Thus, tracking calcite spatial distributions and concentrations over time will be a focus of future ecosystem research as it relates to climate change. While this work may not require additional spectral coverage in the future, it does require accurate sensor calibration and stability monitoring.

Another phytoplankton genus with a distinctive spectral signature is *Trichodesmium*, a cyanobacterium. *Trichodesmium* have gas-filled vacuoles or trichomes, elevated specific absorption coefficients below 443 nm, and uniformly high particle backscatter coefficients in the visible spectrum. Trichodesmium is nitrogen-fixing and can bloom in areas of low ambient nitrate. Westberry et al. (2005) found that if the concentration of trichomes is sufficiently high (3200/l), detection by SeaWiFS is possible (and a sensor with greater SNRs could potentially detect lower concentrations). Westberry and Siegel (2006) mapped the global distribution of *Trichodesium*, which was consistent with global geochemical inferences made by Deutsch et al. [2007], and estimated that the blooms fix 60 TgN/yr which is a four- to six-fold increase over estimates of just 20 years ago (Schlesinger, 1997). Based on the specific absorption spectrum, satellite observations below 412 nm should help improve quantification of *Trichodesium* concentrations.

Going beyond coccolithophores and *Trichodesium* requires the separation of functional groups with different pigment compositions and, therefore, subtle differences in reflectance spectra. Given the limited number of spectral bands that heritage sensors have, separation is a challenge and the uncertainties in the distributions must be high and are difficult to verify because only crude climatologies of species distributions are available. Alvain et al. (2005) used *in situ* databases of reflectance, pigments, functional groups and SeaWiFS reflectances to estimate global open ocean distributions of haptophytes, *Prochlorococcus*, *Synechococcus*-like cyanobacteria (SLC), and diatoms. However, the number of phytoplankton species or size classes that can be estimated is currently limited by the number of SeaWiFS spectral bands.

Enhancing the spectral resolution and spectral range of ocean color measurements can greatly enhance retrieved information on plankton composition. The approach for using such information is referred to as "spectral derivative analysis" and has been demonstrated at 'ground level' by multiple investigators. For example, Lee et al. (2007) used 400 hyperspectral (3 nm resolution) reflectance spectra from coastal and open ocean waters to examine taxonomic signatures in the first- and second-order derivatives. Their analysis indicated very pronounced peaks representing slight spectral inflections due to varying pigment absorption and backscatter characteristics of the water samples. An alternative approach (differential optical absorption spectroscopy) was used by Vountas et al. (2007) and Brachter et al. (2008) and applied to hyperspectral Scanning Imaging Absorption SpectroMeter for Atmospheric CHartographY (SCIAMACHY) imagery (0.2-1.5 nm resolution) to derive global distributions of cyanobacteria and diatoms. These studies show that realistic distributions of functional groups can be extracted from satellite data and underscore the requirement for the ACE ocean radiometer to provide hyperspectral data from the UV to the NIR.

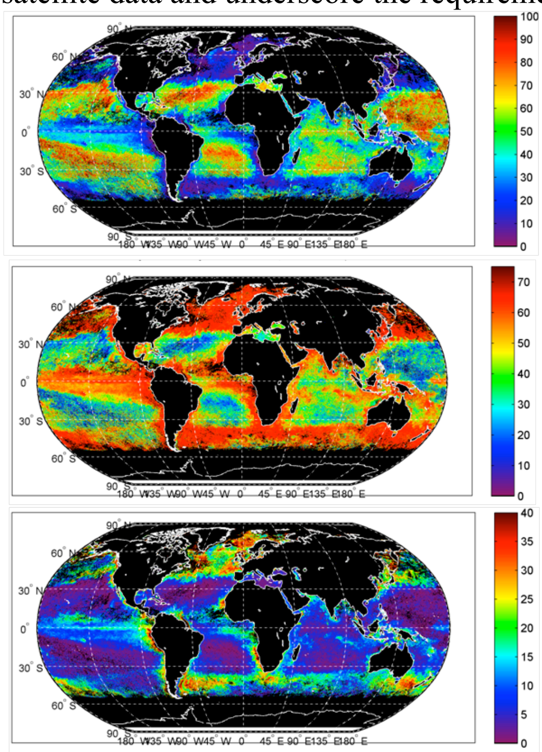

Figure 4. Global distributions of three particle size classes.

In addition to retrieving information on phytoplankton composition through analyses of spectral absorption features, studies have also been conducted on remotely characterizing particle size distributions of natural plankton assemblages. Retrieved particle size distributions provide insight on relationships between scattering coefficients and total particulate organic carbon (POC), as well as the relative contribution of various phytoplankton size classes to bulk standing stocks. Most recently, Kostadinov et al. (2009) extended the work by Loisel et al. (2006) on spectral particle backscatter coefficient to derive global distributions of dominant phytoplankton size classes contributing to total biomass (Figure 4). Here again, higher spectral range and resolution than heritage ocean color bands will significantly improve retrieved properties.

Phytoplankton Physiology

Phytoplankton acclimate to environmental conditions (e.g., nutrients, temperature, and light) on time scales from seconds to seasons. These physiological adjustments influence their absorption spectra, growth rates, C:chl ratios and other characteristics. Intracellular changes in chlorophyll concentration in response to variations in mixed layer light levels alone can span over one order of magnitude, and significantly influence our ability to accurately interpret the satellite chlorophyll record and its relationship to predictions of NPP (see above). Behrenfeld et al. (2008) demonstrated phytoplankton physiological variability was quantified from remote sensing ratios of absorption and scattering properties and provides an illustration of the magnitude of this effect. However, accurate estimation of physiological variability requires increased spectral information.

In addition to light effects on phytoplankton acclimation states, the *degree of nutrient stress* (mild, severe) and the *type of nutrient stress* (e.g., N, P, Fe) contribute a physiological signature to remotely derived pigment fields and will certainly be influenced by changing climate forcings on upper ocean ecosystems. One nutrient stress of particular interest is that of iron limitation. The role of iron as a major factor limiting global phytoplankton concentrations and primary production (Martin and Fitzwater, 1988) has been studied through a number of iron enrichment experiments and modeling studies of aeolian dust transport and deposition (see the ocean-aerosol interaction chapter). Diagnostic indicators of iron stress have also been developed for field deployments, including expression of the photosynthetic electron acceptor, flavodoxin, which replaces ferridoxin under low iron conditions (LaRoche et al., 1996), and unique fluorescence properties of the oxygen-evolving photosystem II complex associated with iron stress (Behrenfeld et al. 2006). From this field-based fluorescence study, Behrenfeld et al. (2006) predicted that satellite fluorescence measurements may provide a means for assessing global distributions of iron stress. In a subsequent study, Behrenfeld et al. (2009) used MODIS fluorescence line height (FLH) data to calculate global fluorescence quantum yields (ϕ), corrected for effects of pigment packaging and non-photochemical quenching, and demonstrated a strong correspondence between elevated ϕ values, low aeolian dust deposition, and model (Moore et al., 2006; Moore and Braucher, 2008, Wiggert et al., 2006) predictions of iron limited growth (Figure 5). These studies further demonstrate the potential for extracting basic information on ecosystem properties far beyond simply measuring chlorophyll-a and are significant design drivers for ACE.

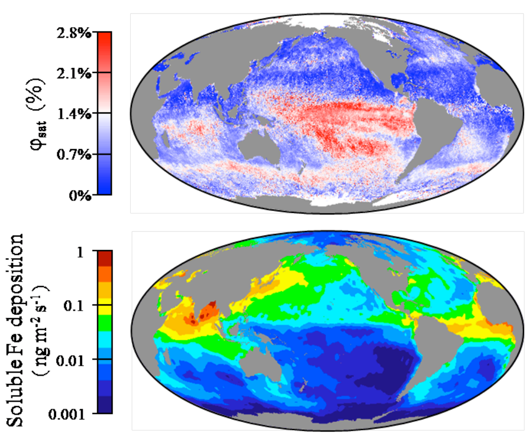

Figure 5. Chlorophyll fluorescence yield (top) as an indicator of soluble iron deposition (bottom; model).

Near-shore and Estuarine Processes

Unlike the SeaWiFS and MODIS (sensors designed for open ocean scientific objectives), the ACE science objectives also involve optically complex ocean margins, the land-sea interface, and larger estuarine systems, and must be capable of supporting coastal management and environmental monitoring requirements as well. These areas form the interface between the terrestrial and open ocean provinces and are the sites of very high primary production rates and biogeochemical transformations of carbon, nitrogen, and phosphorous. These processes are particularly important where freshwater discharge from major terrestrial drainage basins and or/population centers are focused, e.g., Mississippi River delta, Chesapeake Bay, San Francisco Bay, Gulf of Maine, Pamlico Sound, and Pudget Sound. There is considerable debate within the science community as to what fraction of global marine primary production and carbon sequestration actually occurs in these areas and adjacent continental shelves and the “continental shelf pump”(Tsunagai et al., 1999, Yool and Fasham, 2011, and Mueller-Karger et al., 2005). Muller-Karger et al. estimated that the continental margins account for more than 40% of the global ocean carbon sequestration. However, satellite primary production algorithms do not work in many continental shelf and shallow water regions like the U.S. southeast shelf (Signorini et al., 2005). Deriving more accurate estimates of primary production and related quantities in complex coastal regions is a primary ACE science objective.

Other ACE requirements are associated with water quality and red tides. Eutrophication, a depletion of water column oxygen due to the decay of high concentrations organic matter often resulting from enhanced agricultural/sewage runoff nutrient loads, is a serious problem in many coastal regions. The Mississippi River outflow hypoxic or “dead zone” is one highly publicized example (Goolsby, 2000). This condition has a significant impact on ecosystem health, commercial fisheries, and even tourism. In some cases like the Baltic Sea, the events are linked to surface blooms of nitrogen-fixing cyanobacteria which can be detected from satellite (Kahru et al., 2007). In other cases, like the U.S. Gulf coast, there is no strong correlation between surface chlorophyll and hypoxia (Walker and Rabalais, 2006) in which case a sensor more capable than the present day instruments may facilitate new detection approaches. While not necessarily related to eutrophication, harmful algal blooms (HABs) also affect fisheries and are a threat to public health. Kahru and Mitchell (1998) showed that spectral coverage between 340-400 nm is necessary for detecting red tides and more recent studies have focused on utilizing the MERIS 710 nm band (Gower et al., 2005). SeaWiFS and MODIS do not have these wavelengths. Groups within NOAA responsible for red tide monitoring are currently using MERIS data to refine detection algorithms (Wynne et al., 2008). The ACE ocean radiometer should provide capabilities needed to support the most advanced HAB detection algorithms.

In these waters, pigment and particulate complexes are more diverse and concentrated making the spectral reflectances more varied (e.g., IOCCG, 2000). As a result, the spectra are amplified in the red portion of the spectrum and depressed in the UV and blue. Heritage sensors did not exploit applications in the green and red portions of the spectrum. In fact, some MODIS ocean bands saturate in turbid waters, so care must be taken in specifying saturation radiances. Bands in the near-infrared (NIR) were designed for aerosol corrections. However, turbid waters have finite reflectances in the NIR that compromise the aerosol correction resulting in over-corrections. Over the past decade, a number of algorithms to remove or avoid this problem have been developed, e.g., Siegel et al. (2000) using NIR bands and Wang and Shi (2005) using MODIS shortwave infrared (SWIR) bands. For the 2009 SeaWiFS reprocessing, the latest NIR-based aerosol correction scheme resulted in significant improvement in derived product data quality in areas like the Chesapeake Bay (Bailey et al., submitted; Werdell et al., submitted). As Werdell et al. point out, the MODIS SWIR bands do not have adequate signal-to-noise ratios (SNR) to do the turbid water aerosol correction well. For ACE, SWIR bands with adequate SNRs will be required (see Appendix X). Also, the aerosols in many coastal regions absorb radiation, and current algorithms do not handle these corrections. ACE ocean radiometer observations in the near-UV, polarization measurements from the ACE polarimeter, and aerosol height measurements from the

ACE lidar coupled with improved aerosol models will greatly improve ocean color retrievals in the complex atmosphere situations.

Over the past few years, the NASA OBBP recognized the need for expanding its science objectives into near-shore and estuarine waters and has supported this new emphasis through research solicitations, in situ instrumentation development, incorporation of high spatial resolution data from MODIS (250 and 500 m bands) and MERIS (300 m) into the SeaWiFS Data Analysis System (SeaDAS) software (NASA freeware developed and distributed by the NASA Ocean Biology Processing Group at Goddard Space Flight Center), etc. This research and development needs to continue to further lay the foundations for the ACE mission.

Physical-Biological Interactions

There are many ways in which physical processes influence biological processes. These include not only ocean dynamical processes like coastal and equatorial upwelling, vertical mixing due to physical stirring and buoyancy effects, ocean frontal circulation, horizontal advection, etc., but also meteorological conditions such as cloud cover, surface winds, aeolian transport and deposition of dustborne nutrients (iron), etc. These processes modulate the flux of nutrients into the euphotic zone and illumination, which together regulate photosynthesis and other geochemical reactions. Most of these processes have been incorporated into coupled circulation-biogeochemical models either on regional or global scales. There is a huge published literature (theoretical, observational, and model-based) on these topics, particularly on physical forcing of biogeochemistry. However, until recently, the feedbacks of biogeochemistry on ocean dynamics have not been considered or were thought to be of secondary importance. Also, many of the biogeochemical feedbacks are linked to aerosol and cloud properties and are discussed in the ocean-aerosol interaction chapter of this document

Biogeochemical feedbacks on ocean circulation are principally effects associated with radiation absorption near the surface that affects stratification, sea surface temperature, and air-sea heat exchange. Some early studies using satellite ocean color data highlighted "penetration radiance" (Lewis et al., 1990 and Ohlmann et al., 1996) which is the radiance that penetrated through the mixed layer and is, therefore, not available to the coupled ocean-atmosphere system. The penetration of visible light is mostly determined by phytoplankton pigment concentrations, dissolved constituents, and particle concentrations. In low concentration waters like the western Pacific warm pool where the mixed layer is shallow, this radiant flux can be 10-15% of the incident solar irradiance (Siegel et al., 1995; Ohlman et al., 1996). In areas where pigment concentrations are high, more sunlight is absorbed near the surface resulting in warmer temperatures. A consequence of sunlight absorption by phytoplankton is a global amplification of the seasonal cycle of SST (Frouin et al., 2000). The related changes in surface layer temperature and stratification modify surface circulation and SST patterns at levels substantial enough to impact atmospheric circulation, particularly in the tropics (Murtugudde et al., 2002; Shell et al., 2003).

Science Questions and Objectives

To summarize, the science objectives of the ocean biogeochemistry community have expanded remarkably over the past twenty years. This progress has been greatly facilitated by data sets from SeaWiFS and MODIS, advances in marine optics (theoretical and experimental), and a growing concern about the impacts of climate change on marine ecosystems. These new objectives require much more robust measurement systems (see text below for details), especially in terms of spectral coverage. From the discussion above, the following set of ocean science questions are being posed for the ACE mission.

- ***SQ-1:*** What are the standing stocks, composition, & productivity of ocean ecosystems? How and why are they changing?
- ***SQ-2:*** How and why are ocean biogeochemical cycles changing? How do they influence the Earth system?
- ***SQ-3:*** What are the material exchanges between land & ocean? How do they influence coastal ecosystems, biogeochemistry & habitats? How are they changing?
- ***SQ-4:*** How do aerosols & clouds influence ocean ecosystems & biogeochemical cycles? How do ocean biological & photochemical processes affect the atmosphere and Earth system? These questions link directly to Question 4 of the Ocean-Aerosol Interactions element of the ACE program.
- ***SQ-5:*** How do physical ocean processes affect ocean ecosystems & biogeochemistry? How do ocean biological processes influence ocean physics?
- ***SQ-6:*** What is the distribution of algal blooms and their relation to harmful algal and eutrophication events? How are these events changing?

These questions are directly related to the objectives of the NASA Ocean Biology and Biogeochemistry Program as outlined in its long-term planning document, *The Earth's Living Ocean, The Unseen World* (NASA OBB Working Group, 2007).

The Human-Ocean Relationship and Societal Benefits

For Earth's entire history, only one life form has ever existed with the capacity to intentionally modify the role of ecosystems on the global environment: *humans*. We are the ultimate caretakers of this planet and it is upon our shoulders that the well-being of the biosphere rests. Our recognition of this responsibility, however, is recent – emphasized by escalating impacts of an ever-growing human population. In addition and despite a long history of technological advancement, we remain intimately dependent on the biosphere's highly interlaced food webs for our well being. Complex ocean ecosystems provide habitat and natural resources that nurture biodiversity, interact with geochemical and physical systems in the cycling of carbon and other elements, and play an essential role in the regulation of climate over annual to geologic time scales that contributes importantly to the habitability of our planet. At the same time, ocean ecosystems are fragile and highly susceptible to environmental change. One must only look at the mass extinction events in Earth's history to fully appreciate the delicate balance of species diversity and ecosystem resilience and to understand its dependence on stability in climate and biological conditions. Today, threats to ocean ecosystems come not only from natural sources, but from human activities as well, with the human component becoming ever more prominent and well documented. As caretakers of this unique living planet, we are charged with the responsibility of understanding causes and effects of global change and protecting the diversity and invaluable services that the global oceans provide.

Understanding functional relationships within the living ocean, along with ocean-land-atmosphere feedbacks, represents a major challenge to the science community and one to which the ACE mission is particularly well poised to contribute greatly. Through its advanced observation sensor suite, this mission will allow better description and prediction of Earth system mechanisms affected by natural and anthropogenic climate changes, and assessment of how these processes feed back on the overall Earth system over time. At the same time, the ACE mission will provide a more diverse set of capabilities and data products of higher quality in coastal regions than current sensors, e.g., harmful algal bloom detection, suspended sediment concentrations, and carbon pools. The improved understanding and measurement capabilities will enable informed national policy, improved resource management practices, and decreased threats to our economy, health, safety, and national security.

Approach

Addressing the key outstanding science questions for ocean ecosystems requires significant advances in remote sensing capabilities beyond heritage sensors, improvements in strategies to remove contamination of ocean color signals by the atmosphere, and well-developed field- and on-orbit calibration and validation approaches. With the suite of ACE sensors and their advanced capabilities, more accurate- and a broader set of key ecosystem properties can be characterized globally on weekly to shorter time scales. Some of these properties are essential for answering all of the science questions outlined above, while others are targeted toward advancing understanding of a particular science issue. In some cases, the observational data largely functions to inform an overarching model, but in all cases the required set of retrieved properties creates the link between the ***Science Questions*** and ***Measurement and Mission Requirements***.

SQ-1 (Ocean Ecosystems) Approach: Quantify phytoplankton biomass, pigments, and optical properties, assess key phytoplankton groups (e.g., calcifiers, nitrogen fixers, carbon export), and estimate particle size distribution and productivity using bio-optical modeling, chlorophyll fluorescence, and ancillary data on ocean physical properties (e.g., SST, MLD, etc.). Validate these retrievals from pelagic to nearshore environments.

SQ-2 (Ocean Biogeochemical Cycles) Approach: Retreive phytoplankton biomass and functional groups, POC, PIC, DOC, PSD and productivity from remotely sensed ocean properties. Validate these retrievals from pelagic to nearshore environments. Assimilate ACE observations in ocean biogeochemical models to provide fields for missing observations (cf., air-sea CO_2 fluxes, export, pH, etc.).

SQ-3 (Land-Ocean Interactions) Approach: Quantify particle abundance, dissolved material concentrations and their physical and optical properties. Validate these retrievals from coastal to estuarine environments. Compare ACE observables with ground-based and model-based land-ocean exchange in the coastal zone, physical properties (e.g., winds, SST, SSH, etc), and circulation (ML dynamics, horizontal divergence, etc).

***SQ-4* (Atmosphere-Ocean Interactions) Approach**: Quantify ocean photobiochemical and photobiological processes and atmospheric aerosol loads and distributions. Combine ACE ocean and atmosphere observations with models and other remotely retrieved fields (e.g. temperature and wind speed) to evaluate (1) air-sea exchange of particulates, dissolved materials, and gases and (2) impacts on aerosol and cloud properties. Conduct field sea-truth measurements and modeling to validate retrievals from the pelagic to near-shore environments.

***SQ-5* (Bio-physical Interactions) Approach)**: Compare ACE ocean observations with measurements of physical ocean properties (winds, SST, SSH, OOI assets, etc.) and model-derived physical fields (ML dynamics, horizontal divergence, etc.). Estimate ocean radiant heating and assess feedbacks. Validate from pelagic to nearshore environments.

***SQ-6* (Algal Blooms and Consequences) Approach)**: Measure key phytoplankton biomass, pigments and key group abundance including harmful algae. Quantify bloom magnitudes, durations, and distributions, assess inter-seasonal and inter-annual variations, and compare variability to changing environmental/physical properties. Validate these retrievals from pelagic to nearshore environments.

Measurement & Mission Requirements

SeaWiFS and MODIS ocean requirements were defined in the 1980s with an emphasis on global open ocean observations of chlorophyll-a. Both sensors addressed major deficiencies in the proof-of-concept CZCS design and calibration/validation programs, e.g., the addition of NIR bands for atmospheric correction and mission-long on-orbit and field calibration measurements. Since then, the ocean optics and marine biology communities have developed capabilities and applications that far exceed the spectral coverage of these sensors and experience using these sensors has provided many "lessons learned". Also, development of climate data records requires consistent sets of spectral bands and stringent mission-long stability specifications. Together, this cumulative experience has highlighted a number of new requirements, including the following enhancements which are incorporated into the ACE ocean measurement requirements. A table is provided in Appendix X that lists 26 discrete bands and specific applications of each. Note that the table includes the SeaWiFS and MODIS bands for continuity.

1. Major advances in global ocean biological studies have been realized through the development of spectral inversion algorithms. These algorithms allow the simultaneous and mutually consistent retrieval of multiple in-water properties, including phytoplankton absorption, absorption by colored dissolved organic material, and particulate backscattering coefficients. SeaWiFS and MODIS do not provide adequate spectral coverage for optimizing the inversions.
   <u>Requirement:</u> 19 bands at specific center wavelengths between 360-748 nm characteristic of key constituent absorption and scattering features. (**Related Science – *SQ-1, SQ-2, SQ-4, SQ-5, SQ-6***)

2. The addition of a 412 nm band into SeaWiFS and MODIS has provided a first look at the separation of chlorophyll-a and CDOM using satellite ocean color imagery. Within the UV, CDOM dominates light absorption for nearly all natural waters and improvements in separation between chlorophyll-a and CDOM will occur from including measurements of water-leaving radiance in the UV. Requirement: additional bands at 360 and 380 nm . (**Related Science –** ***SQ-1, SQ-2, SQ-3, SQ-4***)

3. Uncertainties in current inversion retrievals by passive sensors can be reduced through simultaneous and independent measurements of particle scattering using active sensors. Recent analyses of CALIPSO data have demonstrated that space-based lidar systems can provide active measurements of subsurface scattering and possibly information on vertical distributions of particles. Requirement: Lidar measurements with parallel and perpendicular retrievals at an ocean-penetrating wavelength and with a vertical resolution of 2 meters subsurface. (**Related Science –** ***SQ-1, SQ-2, SQ-3, SQ-6***)

4. Recent research has shown that phytoplankton fluorescence quantum efficiency can be derived from MODIS fluorescence data and that the quantum efficiency is related to iron limitation or stress. Requirement: Fluorescence line height bands consistent with the MODIS fluorescence line height bands for time series continuity. (**Related Science –** ***SQ-1, SQ-2, SQ-5, SQ-6***)

5. The research community has also explored the identification of phytoplankton functional groups using SeaWiFS and MODIS, but with high uncertainties. Recent analyses using hyperspectral SCIAMACHY on Envisat have demonstrated the promise of spectral derivative analyses. Requirement: 5 nm resolution data from 360 to 755 nm. (**Related Science –** ***SQ-1, SQ-2, SQ-6***)

6. Studies in optically-complex coastal waters have identified limitations in the use of blue and green bands for quantifying chlorophyll. Requirement: Additional bands in the red, and near-infrared, including 700-750 nm range, are necessary. (**Related Science –** ***SQ-3, SQ-6***)

7. Accurate satellite retrievals of water leaving radiances require robust and accurate corrections for atmospheric contributions to top-of-atmosphere (TOA) radiances. In short, the ocean color problem is one of low 'signal to noise', as greater than 90% of TOA radiances can be from the overlying atmosphere. In some circumstances (e.g., presence of Asian or African dust) current atmospheric corrections suffer from inadequate information on these aerosol optical properties and their vertical distribution. Requirement: Lidar 'curtain' measurement of aerosol distributions with 0.5 km vertical resolution and polarimeter broad spatial coverage to retrieve aerosol heights and single scatter albedo. Include UV bands (Item 2 above) to assist in the detection and atmospheric correction of absorbing aerosols. (**Related Science –** ***All SQ's***)

8. Certain required bio-optical bands overlay water vapor absorption features making corrections necessary. Requirement: Include an 820 nm band to quantify water vapor concentration. (**Related Science – *SQ-1, SQ-4,SQ-6***)

9. Programmatic research objectives oriented towards turbid coastal waters must address finite reflectances in the NIR bands which compromise the aerosol correction. Requirement: SWIR bands at 1245, 1640, and 2135 nm with substantially higher SNRs than the equivalent MODIS bands. (**Related Science – *SQ-3, SQ-6***)

10. The direct lunar calibration (Earth-viewing optics only) and in situ vicarious calibration of SeaWiFS, in particular, successfully demonstrated the climate quality ocean biology data sets necessitate highly accurate independent temporal stability monitoring (0.1% stability knowledge over the duration of the mission) and gain adjustments, respectively. The vicarious calibration required a multi-year time optical mooring deployment to establish stable gain factors. Requirement: Monthly lunar views at a fixed 7° lunar phase angle and at least one long-term vicarious calibration time series. (**Related Science – *All SQ's***)

11. Concurrency of global data products is required to address many of the ACE Ocean Ecosystems science questions and for ocean color data processing. These observations include SST, SSH, vector winds, MLD, precipitation, and O_3 and NO_2 concentrations. Requirement: Concurrency of operational satellite data and model output products. (**Related Science – *All SQ's***)

Other sensor requirements address sun-glint avoidance (sensor tilting), polarization sensitivity, SNRs, image quality (straylight, stripping, crosstalk), 2-day global coverage frequency, data quantization, and saturation radiances. To achieve the radiometric accuracy requirements of the inversion algorithms, well-developed and tested technologies and methodologies for prelaunch sensor characterization must be established in advance of flight unit testing. When all the requirements for passive ocean radiometry are tallied, the comparison with heritage sensors is striking, particularly with respect to spectral coverage (Figure 6).

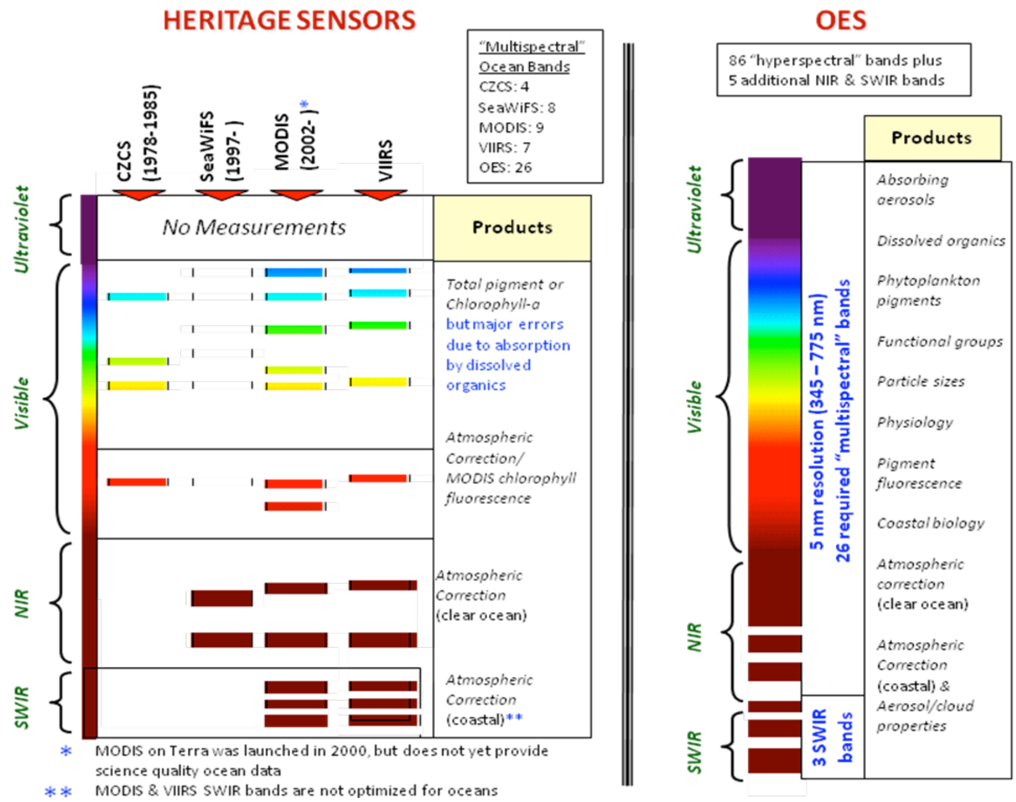

Figure 6. Comparison of spectral coverage of heritage sensors and the OES.

Calibration, Validation,and Observations in the Field

Observations made *in situ* are an essential and integral part of the ACE mission. Field work will consist of observations useful for calibration and validation (e.g. measurements of optical properties), but will also include measurements essential to answering the science questions that are not possible from the ACE spacecraft-based instruments. An example of these sorts of observations would be measurements of export flux (***SQ-2***) which occurs below the surface layer of the ocean and is thus not directly observable by remote sensing. Field observations will also be critical in the prelaunch phase for the purpose of developing algorithms or identifying proxy measurements that will employ the new capabilities of the ACE spaceborne instruments. Previous experience with SeaWiFS, MODIS, and related ocean color radiometers indicates that continuous assessment of calibration and validation of products, combined with periodic reprocessing of complete mission data sets, is necessary throughout the lifetime of the mission. Sustained mission-lifetime measurements will take place at selected time series sites for purposes of vicarious calibration (mission requirement 8) and product validation, and these will be augmented by measurements made on cruises and moorings of opportunity, and in intensive field campaigns. Product validation and algorithm development will be facilitated by the continuation of the NASA SeaBASS database, which stores bio-optical (and now biogeochemical) data collected concurrently with satellite overpasses.

New sensor capabilities will require corresponding capabilities in the field. A road map for technology development is being developed by the community that describes necessary advancements required to make best use of the future ACE sensor suite in solving the science questions laid out by the ACE Ecosystems working group. Figure 7 shows the current state of the art for a list of parameters that are required for particular SQs, in terms of analytical capability and deployment technology. For the ACE mission this includes biogeochemical parameters in addition to the traditionally measured radiometric quantities. Pressing needs here include extension of currently measured radiometric and inherent optical properties into the UV and further into the NIR.

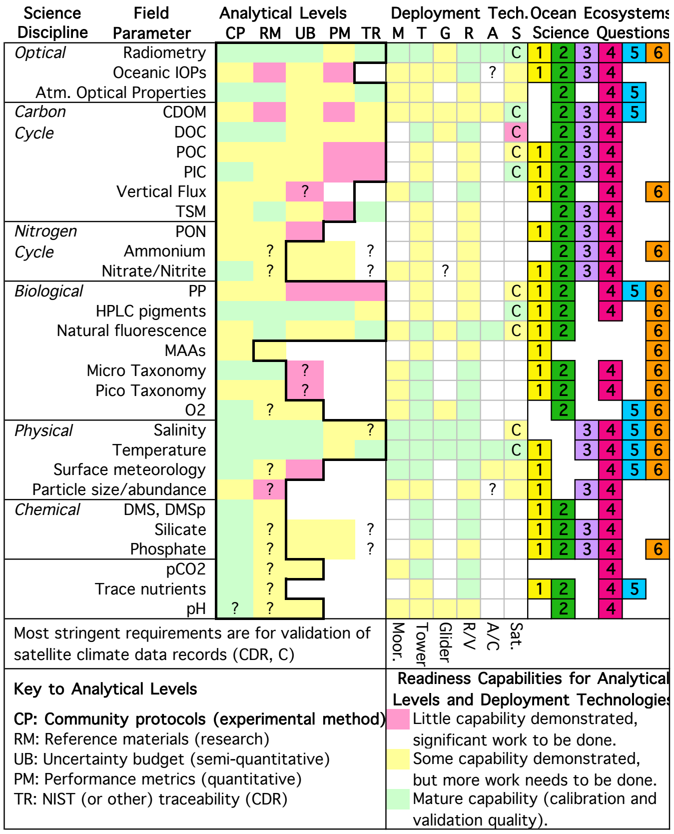

Figure 7. Ocean in situ/laboratory measurements requirements. The "?" implies the status is not known.

Intensive field campaigns will be designed to address particular interdisciplinary questions with shipborne measurements complementing the ACE sensor suite. Specific proposed cruises/topics are being discussed by the community now. Campaigns will be designed to take maximum advantage of suborbital resources (e.g. airborne and shipborne measurements) to make best use of the available remote sensing data. Topics will include ocean-aerosol interactions in coastal and open-ocean areas where atmospheric correction due to dust and other terrestrial aerosols has been challenging for current sensor technology.

One strategy for efficiently pursuing ACE goals in interdisciplinary field campaigns is to cooperate with national and international coordinating groups who are proposing large field programs. Examples of these include OCB (Ocean Carbon and Biogeochemistry, http://www.us-ocb.org/), addressing ***SQ-1*** & ***SQ-2***; SOLAS (Surface Ocean-Lower Atmosphere Study, http://www.us-solas.org/), addressing ***SQ-4***; and CLIVAR/Carbon Repeat Hydrography Project (http://ushydro.ucsd.edu/), addressing ***SQ-2*** & ***SQ-5***.

GLOSSARY OF ACROYNMS

ACE Aerosol-Cloud-Ecosystem Mission

CDOM	Colored Dissolved Organic Material
CZCS	Coastal Zone Color Scanner
DOC	Dissolved Organic Carbon
ML	Mixed Layer
MLD	Mixed Layer Depth
MODIS	Moderate Resolution Imaging Spectroradiometer
NIR	Near Infra-Red
OOI	Ocean Observing Initiative
PIC	Particulate Inorganic Carbon
POC	Particulate Organic Carbon
PSD	Particle Size Distribution
SeaWiFS	Sea-Viewing Wide Field of View Sensor
SNR	Signal-to-Noise Ratio
SQ	Science Question
SSH	Sea Surface Height
SST	Sea Surface Temperature
SWIR	Short-Wave Infra-Red
TOA	Top Of Atmosphere
UV	Ultra-Violet

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