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Putting Together the Big Picture:
Remote-sensing Observations of Ocean Color

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Introduction

Observations of ocean color from space have been part of the U.S. JGOFS strategy for discerning temporal and spatial variations in upper-ocean productivity on the global scale since the first planning workshops for a U.S. global ocean flux program (National Academy of Sciences, 1984). From the start, remote measurements of near-surface chlorophyll a concentrations were envisaged as the major tool for extrapolating upper-ocean chemical and biological measurements in time and space and linking calculations of new and primary production with the flux of particulate material through the water column.

In 1986, researchers at the U.S. National Aeronautics and Space Administration (NASA) Goddard Space Flight Center published the first monthly composite of images from the Nimbus-7 Coastal Zone Color Scanner (CZCS), an ocean color instrument that had been in orbit since 1978. These images showed basin-scale views of phytoplankton chlorophyll distributions for the first time (Esaias et al., 1986). These new images, coupled with the JGOFS requirement for satellite ocean-color measurements, rejuvenated interest at NASA and other space agencies in launching successors to the CZCS.

CZCS stopped operating during 1986. By spring 1988, when the initial planning workshop for the international North Atlantic Bloom Experiment (NABE) was held, it was apparent that data from a new sensor would not be available for the first JGOFS field program, scheduled to begin in the North Atlantic in spring 1989. Because of launch delays and other technical problems, the next ocean-color instrument, the Sea-viewing Wide Field-of-view Sensor (SeaWiFS), was not launched into space until August 1997. Thus satellite ocean-color observations were available only for the Antarctic Environment and Southern Ocean Process Study (AESOPS), the final U.S. JGOFS field program.

Nevertheless, satellite and aircraft ocean-color measurements had an important role in JGOFS. First, retrospective analyses of CZCS chlorophyll images were important for planning all of the U.S. JGOFS process studies (Feldman et al., 1992). Second, aircraft remote-sensing measurements were part of the field studies in the North Atlantic, equatorial Pacific and Arabian Sea. Third, SeaWiFS data collected during AESOPS were used to extrapolate *in situ* measurements made during the field study, making possible a basin-scale calculation of primary production and particulate organic carbon (POC). Finally, data from CZCS, SeaWiFS, the Ocean Color and Temperature Sensor (OCTS), and the Polarization and Directionality of the Earth's Reflectances (POLDER) sensor are contributing substantially to the analyses and modeling studies of the U.S. JGOFS Synthesis and Modeling Project (SMP) (see Doney et al., this issue).

Satellite ocean-color sensors provide the only global ocean measurements on roughly monthly time scales that are directly related to biogeochemical distributions and processes. Thus, new satellite ocean color sensors, such as the Moderate-resolution Imaging Spectroradiometer (MODIS) launched by NASA on the Terra spacecraft in 1999, will play an important and perhaps extended role in future studies of global biogeochemical cycles (Yoder, 2000). Future sensors may be able to provide remote-sensing data on key phytoplankton taxonomic groups, the distribution of POC and chromophoric dissolved organic matter (CDOM) and chlorophyll fluorescence and an index of photosynthetic efficiency.

Background

"Ocean color" is a shorthand term for a specific set of *in situ* measurements from instruments on aircraft or spacecraft used to determine the radiance backscattered from water and across the air-sea interface at some or many spectral bands. A more formal name for ocean color is ocean spectral reflectance (R) or water-leaving spectral radiance (L_w). Normalized water-leaving radiance (nL_w) and Remote Sensing Reflectance (R_{rs}) are variations of L_w and R that take into account sun angles and atmospheric contributions. Water-leaving radiance is proportional to the backscatter coefficient (bb) and inversely proportional to the absorption coefficient (a) in the equation L_w @ b_b/a. The contribution of backscatterers and absorbers are basically additive so that a simple expansion of the basic equation above provides a realistic and useful conceptual and quantitative description of water-leaving radiance.

The principal absorbers at the wavelengths of current satellite sensors are water molecules, phytoplankton pigments, CDOM and particulate detritus. The latter two components have similar absorption properties and are often lumped together. Important backscatterers are water molecules, particularly at comparatively short (blue) wavelengths, phytoplankton and detrital particles, and non-biogenic sediments in coastal waters. Bacteria, viruses, colloids and small bubbles are potentially important components of the backscattering signal; there is much current debate as to their relative contributions.

The U.S. JGOFS Air Corps: Ocean-Color Measurements At Low Altitude

Because satellite ocean-color data were not available at the time, aircraft measurements were used to support some cruise legs during U.S. JGOFS process studies in the North Atlantic, equatorial Pacific and Arabian Sea. Open-ocean field programs are difficult to support with aircraft observations because of the logistical problems posed by the long distances between airports and the study sites. The only aircraft with long-distance capabilities that was routinely available to the JGOFS program was the P-3 operated by the NASA Wallops Flight Facility (Figure 1).

NASA P-3 aircraft flew during portions of the JGOFS pilot study in the North Atlantic in 1989 (NABE), the Equatorial Pacific Process Study (EqPac) in 1992 and the Arabian Sea Process Study in 1994-96. The P-3 flies at low altitude (150 m off the sea surface) and thus below cloud cover. Because of the low altitude, data are collected and displayed along track lines rather than as images.

The primary instrument on the aircraft during the U.S. JGOFS field studies was the NASA Airborne Oceanographic LIDAR (AOL) sensor (Hoge et al., 1986). The AOL is an active sensor that, during the JGOFS overflights, acquired laser-induced fluorescence with excitation at 355 and 532 nm from constituents in the water in contiguous bands 10-nm wide between 390 and 750 nm (Figure 2). The 355 nm laser excites CDOM fluorescence over a broad spectral region centered near 450 nm. The 532 nm laser induces chlorophyll *a* fluorescence at 685 nm and phycoerythrin fluorescence in bands centered at 560 and 590 nm. To remove effects of variability in attenuation properties in the upper layer of the ocean along the flight path, the fluorescence signals are normalized by the water Raman backscatter resulting from the laser inducing the fluorescence.

In addition to active and passive optical measurements, sea-surface temperature measurements were made with a Heimann infrared radiometer and recorded by the AOL along with the laser-induced fluorescence data. The P-3 also deployed airborne expendable bathythermographs (AXBTs) for vertical temperature profiles.

Data collected during each flight were rapidly processed and results sent by fax, along with a brief report, to oceanographic ships in the study area as well as to other investigators within a few hours of collection. During NABE, AXBT temperature profiles, estimates of chlorophyll *a* concentrations and other data were sent back to a Harvard University ocean modeling group that used the information to set initial conditions for mesoscale models of eddy circulation within the 47°N, 20°W study area (Robinson et al., 1993). In turn, results of model simulations were sent out to the ships and used to help determine and adjust sampling protocols.

In addition to the real-time support for the field studies that the aircraft measurements provided, more extensive analyses of the data helped to demonstrate and quantify the importance of mesoscale variability in the North Atlantic and the close relationship between

Figure 1. *During JGOFS-NABE overflights, the U.S. JGOFS Air Corps and the NASA P-3 airplane on the tarmac in Iceland.*

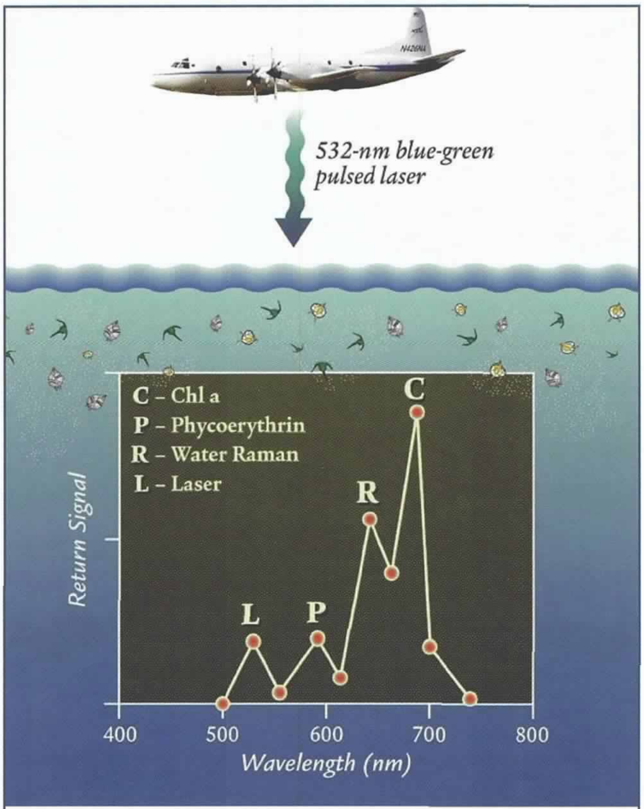

Figure 2. *Schematic diagram of the operation of the Airborne Oceanographic Lidar (AOL) and the detected signals (inset). Laser pulses stimulate phytoplankton chlorophyll* a *and phycoerythrin fluorescence (C and P respectively). The on-wavelength laser return signal (L) is used to estimate particle scattering, and the water Raman signal (R) is used to correct for variable laser penetration depths.*

temperature and variability in phytoplankton chlorophyll (Robinson et al., 1993). The results were also used to help interpret observations from Marine Light in the Mixed Layer (MLML) moorings south of Iceland that were deployed at the same time as the NABE cruises (see Dickey, this issue). Combining the spatial information from aircraft measurements of surface chlorophyll *a* with the temporal information from the moorings showed that a significant component of the variability at the mooring was caused by advection of phytoplankton patches. These studies in the North Atlantic concluded that there were consistent relationships between the mesoscale patterns of physical parameters and chlorophyll *a* distributions.

Real-time aircraft observations also played an important role during EqPac. Researchers and instruments on P-3 overflights in August 1992 observed very high concentrations of phytoplankton associated with a frontal feature near 2°N, 140°W (Yoder et al., 1994). The observations and positions were radioed from the plane to R/V *Thomas G. Thompson*, which was operating nearby. The information was used by the oceanographers aboard ship to find and sample this unusual feature.

Ocean-color remote sensing had an interesting and somewhat controversial role in the U.S. JGOFS Arabian Sea study, contributing to a debate over what causes certain patterns observed in the region. CZCS images of the Arabian Sea (Brock and McClain, 1992) suggested that there was a significant area of intense open-ocean upwelling with high concentrations of chlorophyll *a*. One investigation based on analyses of global CZCS imagery (Yoder et al., 1993) referred to the apparently high chlorophyll concentrations following the southwest monsoon in the Arabian Sea as a "major subtropical anomaly." Although SeaWiFS images show similar patterns, investigators have questioned their interpretation. The question is whether plumes of dust blowing off the nearby desert and over the ocean can lead to inaccurately high results for chlorophyll *a* in remote measurements of ocean color.

Aerosol studies during the Arabian Sea cruises showed that dust concentrations at the ocean surface are not higher during the southwest monsoon than during other seasons (Tindale and Pease, 1999). However, sea-salt aerosol concentrations are exceptionally high because of the strong winds. It is possible that the absorption properties of sea-salt aerosols could produce misleadingly high chlorophyll signals in remote measurements.

Given these data, some investigators have questioned the extent of open-ocean upwelling in the Arabian Sea and the significance of the southwest monsoon period for annual Arabian Sea productivity. Other studies show that open ocean chlorophyll *a* concentrations are at annually high levels during the southwest monsoon (Kinkade et al., 2001), although not as high as inferred from CZCS and SeaWiFS imagery. In summary, satellite ocean-color images of the Arabian Sea may well have overemphasized the significance of the upwelling associated with annual southwest monsoons for annual productivity in the region.

Satellite Observations in the Southern Ocean

Ocean-color data collected over the last two decades has provided key insights into the spatial distribution of phytoplankton blooms and the processes controlling primary production in the Southern Ocean. This information was of material assistance in planning JGOFS field studies in the region. Initial studies using CZCS data and recently more detailed studies using SeaWiFS data (Moore and Abbott, 2000) showed that chlorophyll concentrations are perpetually low over most of the Southern Ocean. The satellite data revealed that phytoplankton blooms are largely restricted to three zones: coastal waters, the marginal ice zone and the major Southern Ocean fronts. Both the European JGOFS transect along 6°W and the AESOPS transect

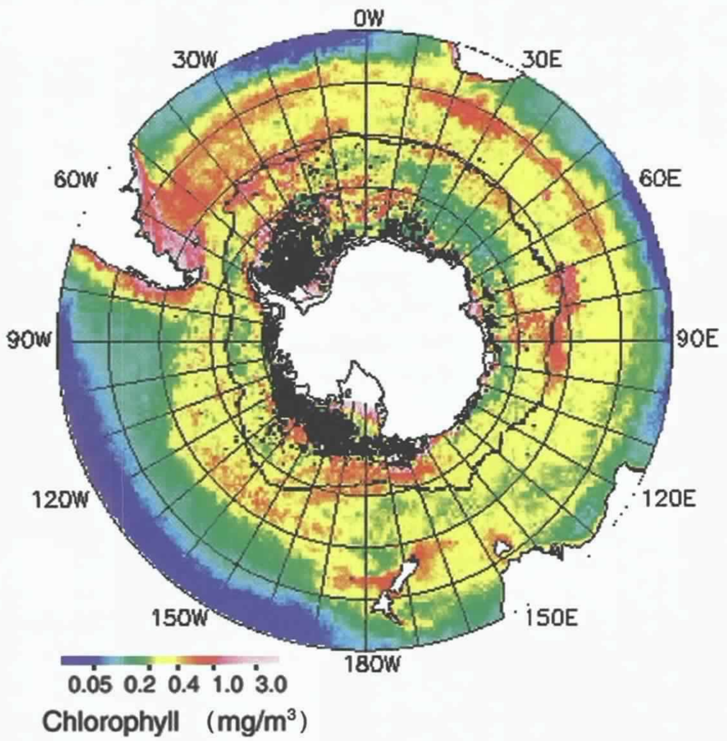

Figure 3. *Distribution of mean chlorophyll* a *concentrations in the Southern Ocean for the month of December, averaged over the first four years of SeaWiFS data (1997–2000), along with the mean position of the Antarctic Polar Front as determined from satellite sea-surface temperature imagery. Areas of elevated chlorophyll* a *occur in coastal waters, in areas of sea-ice retreat and along some parts of the polar front. The band of high chlorophyll concentrations along 40°S south of Africa is also associated with frontal systems and high kinetic energy. SeaWiFS data confirm major features that appear in CZCS imagery but provide much more extensive coverage (adapted from Moore and Abbott, 2000).*

along 170°W took place in regions of frequent phytoplankton blooms associated with the Antarctic Polar Front (Figure 3). The regions where blooms occur are also known to have elevated levels of iron in surface waters. Thus satellite observations have provided indirect evidence supporting the hypothesis that the availability of iron limits phytoplankton growth rates.

Figure 3 depicts the distribution of mean chlorophyll concentrations for the month of December, averaged over the first four years of SeaWiFS data (1997–2000), along with the mean position of the Antarctic Polar Front as determined from satellite sea-surface temperature data. Elevated chlorophyll concentrations are evident in coastal waters, in areas of sea-ice retreat in the Weddell and Ross seas and in some regions along the polar front. The band of high chlorophyll concentrations along 40°S south of Africa is also associated with frontal systems and high eddy kinetic energy. Figure 3 also shows that, in contrast to conditions in the frontal regions, chlorophyll concentrations are generally quite low over the rest of the Southern Ocean.

AESOPS demonstrated the full potential of satellite ocean-color observations as a source of data on the larger spatial context of major field biogeochemical sampling programs and process studies. SeaWiFS images show that the bloom observed from ships at the polar front extended throughout the entire region along the Pacific-Antarctic Ridge, indicating that conditions sampled during the detailed studies conducted along 170°W were representative of a much larger area. The ongoing SeaWiFS mission in conjunction with other current and planned ocean-color sensors provide the best large-scale observations to date for this remote oceanic region and lay the baseline for long-term studies.

U.S. JGOFS Synthesis and Modeling Program (SMP)

SMP investigators and others interested in global biogeochemical cycles are using CZCS, SeaWiFS and other ocean-color sensor imagery to help determine the spatial and temporal variability related to the ocean carbon cycle on a wide variety of scales. The foci of SMP projects (listed at http://www1.whoi.edu/mzweb/resarea.html) include mesoscale variability at the Bermuda-Atlantic Time-series Study (BATS) site, upper-ocean productivity in the four major coastal upwelling systems, interannual variability in the North Atlantic related to North Atlantic Oscillation (NAO) cycles and in the equatorial Pacific related to El Niño-Southern Oscillation (ENSO) cycles, CDOM as a potential carbon sink, extrapolation of POC distributions derived from transmissometer measurements, and large-scale patterns in basin and global imagery.

Three examples illustrate the ways in which satellite ocean-color observations are helping investigators synthesize, model and understand biological components of the ocean carbon cycle and their variability.

Remote Sensing Tools For Ocean Biogeochemistry

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Satellite-borne sensors provide broad spatial and temporal coverage and consistent methodology as well as a powerful capacity for extrapolating, integrating and constraining field observations and modeling results. Repeat coverage allows us to quantify scales of variability otherwise inaccessible outside of process studies. However, remote-sensing measurements are limited in what they can measure, their resolution and their sampling depth, which is usually limited to surface waters in the ocean context. Novel approaches that use both comprehensive comparison of field and satellite observations and new theoretical applications can greatly enrich our use of existing and planned space-based measurements. By assimilating remotely sensed and *in situ* data into circulation models, for example, we can obtain quantitative assessments of relevant ocean parameters, such as subsurface velocity or mixed-layer depth.

What Can We Sense Remotely?

Major oceanographic variables currently measured from space and the sensors designed to measure those variables:

Variable	Sensor
Sea-surface temperature (SST)	AVHRR, MODIS, TMI, ATSR
Sea-surface salinity	(proposed)
Sea-surface height (SSH)	TOPEX/POSEIDON, ERS2
Wind speed and direction	QuickScat, ERS2, SSM/I (speed only)
Chlorophyll concentration	SeaWiFS, MODIS
Fluorescence	MODIS
Aerosols	AVHRR, TOMS, SeaWiFS, MODIS, MISR, ATSR

[Acronyms: Advanced Very High Resolution Radiometer (AVHRR), Moderate Resolution Imaging Spectroradiometer (MODIS), Along-Track Scanning Radiometer (ATSR), Tropical Microwave Imager (TMI), Topography Experiment (TOPEX), European Remote Sensing Satellite (ERS), Special Sensor Microwave Imager (SSM/I), Quick Scatterometer (QuickScat), Sea-viewing Wide Field-of-view Sensor (SeaWiFS), Total Ozone Mapping Spectrometer (TOMS), Multi-angle Imaging Spectro-Radiometer (MISR)]

What Do We Need To Know?

The oceanographic processes and compartments that must be quantified to improve our understanding of ocean biogeochemical cycles are listed below, followed by the pertinent remotely-sensed variable or remote-sensing technique. For highly variable systems, we need platforms that allow higher frequency sampling, such as geostationary platforms.

Oceanographic Process	Variable
Circulation, mixed-layer depth, geostrophic currents	SSH
Air-sea exchange of CO_2	
pCO_2 of ocean	SST, salinity chlorophyll concentration
gas exchange coefficient	wind speed surface roughness
Photosynthesis	chlorophyll concentration irradiance, SST, fluorescence
New and export production	
f-ratio	SST, primary production, NO_3 chlorophyll concentration
supply of new nutrients	heat flux, precipitation
new nutrient uptake	oxygen, heat flux heat storage, SST
plankton community structure (N_2 fixation, calification)	ocean color, compound remote sensing
Carbon species (POC, DOC)	ocean color
Production of radiatively active gases (photochemistry)	ocean color irradiance
Variability, unresolved processes	
eddies	variability in SSH, SST, color, wind vector
forcing events (storms etc.)	wind vector
coastal processes	multispectral ocean color

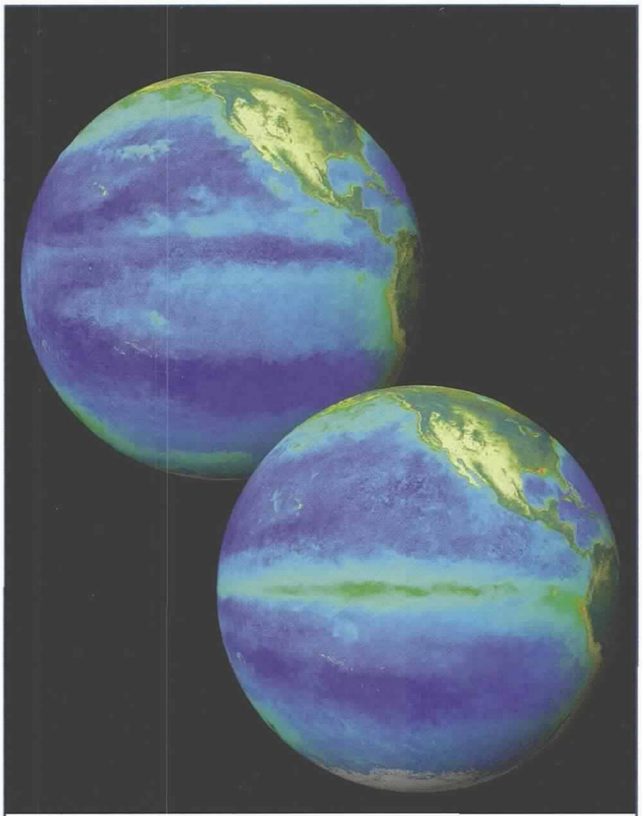

Figure 4. ENSO effects on equatorial Pacific chlorophyll a *concentrations during January (El Niño) and July (La Niña) of 1998. (Image courtesy of the SeaWiFS Project, NASA Goddard Space Flight Center and ORBIMAGE.)*

Investigators have found that the upper ocean in the equatorial Pacific responds dramatically to phases of the ENSO cycle (Figure 4). During the transition from El Niño to La Niña conditions between January and July 1998, SeaWiFS images and *in situ* observations showed a 20-fold increase in surface chlorophyll *a* (from 0.05 to 1.0 mg m^{-3}) along the equator in the central Pacific (Chavez et al., 1999). Calculations based on three years of SeaWiFS images indicate that global ocean primary production increased from 54 to 59 petagrams of carbon per year (1 Pg = 10^{15} grams) in the period following the 1997–98 El Niño, with higher mean chlorophyll concentrations in the equatorial Pacific providing most of the change (Behrenfeld et al., 2001).

Bio-optical and POC measurements during AESOPS provide a second synthesis example. Shipboard measurements from the Ross Sea and Antarctic Polar Frontal Zone were used to develop a simple empirical algorithm linking water-leaving radiance to upper ocean POC concentrations (Stramski et al., 1999). This relationship and SeaWiFS imagery were then used to estimate the total amount of POC (0.8 Pg C at the December peak in the growing season) within the top 100 meters of the entire Southern Ocean south of 40°S.

As a third example, modelers are learning how to assimilate satellite ocean-color data into numerical models and are using the results to help constrain model parameters and to determine whether a particular model structure is consistent with a given set of observations. In recent assimilation experiments using a marine ecosystem model of the central equatorial Pacific Ocean, similar model parameter values were estimated from assimilation of data from EqPac cruises

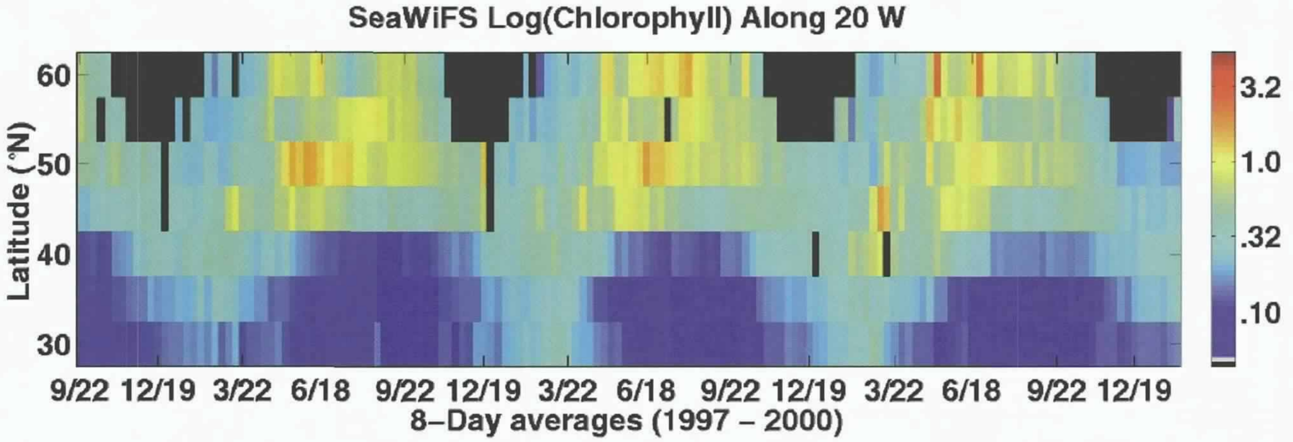

Figure 5. Latitude versus time plot of SeaWiFS chlorophyll (log scale) in the North Atlantic along 20°W longitude. Data are shown in 8-day, 5-degree "bins." Areas shown in black lack data because of cloud cover and low wintertime sun angles at high latitudes.

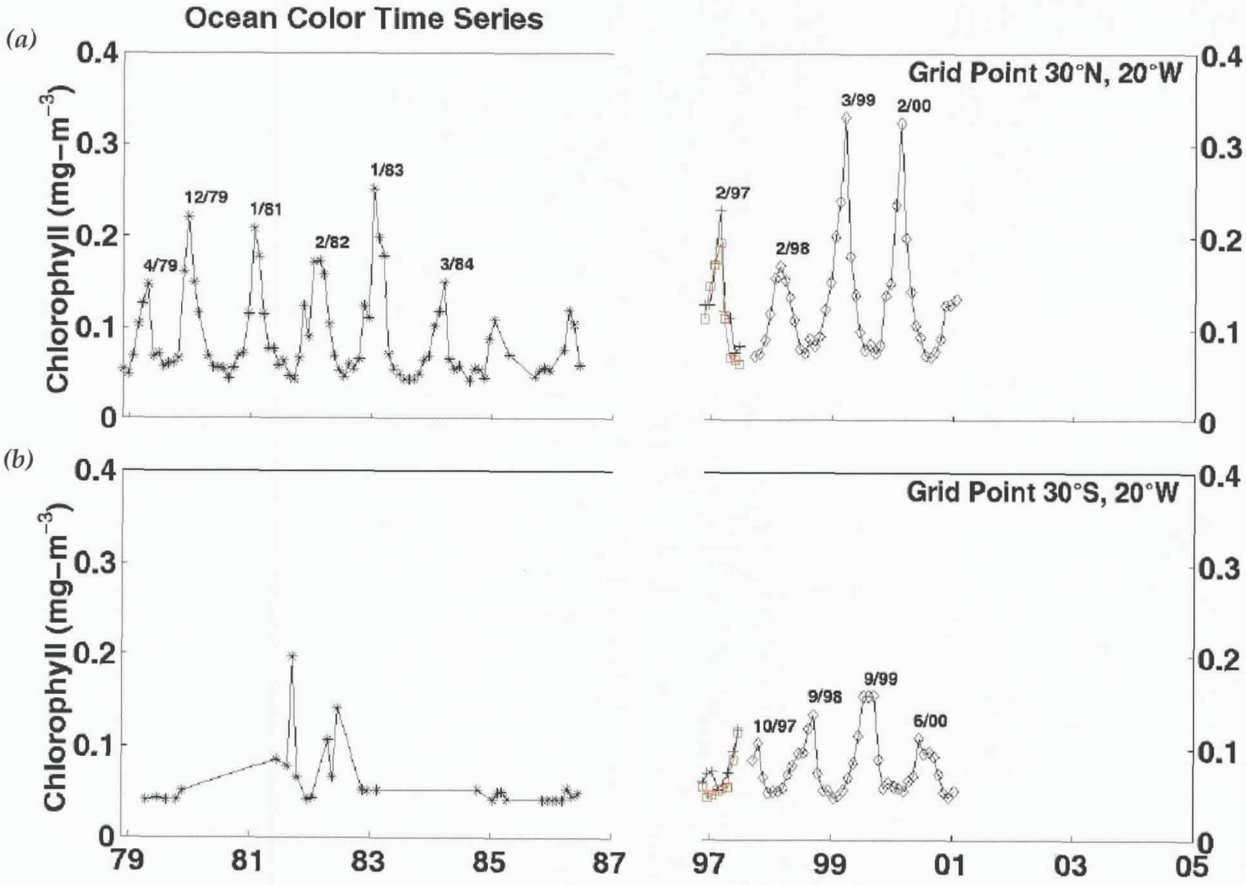

Figure 6. *Chlorophyll time-series data from grid points in the North Atlantic* ***(a)*** *and South Atlantic* ***(b)*** *from four ocean-color sensors: CZCS (1979–1986), POLDER and OCTS (1996–97) and SeaWiFS (1997–2001). Numbers in the figure show months of peak chlorophyll concentration.*

during the 1991–92 El Niño and from SeaWiFS measurements during the 1997–98 El Niño. Assimilation of SeaWiFS data into the model also helped to identify a period during the 1997–98 El Niño when limitation of phytoplankton productivity switched from macronutrients such as nitrogen to micronutrients such as iron. Finally, the SeaWiFS assimilation experiments showed the importance of matching the temporal scales used in models with those represented in data sets to obtain optimum model parameter values (see Doney et al., this issue).

Future Developments

Remote-sensing measurements of ocean color will play a key role in future ocean carbon cycle studies. Aircraft LIDAR techniques that are under development employ a pump-probe technique, which uses multiple laser pulses to determine phytoplankton fluorescence at different photosystem saturation states, to obtain continuous measurements of the maximum rate of photosynthesis and other photosystem parameters along flight lines (Chekalyuk et al., 2000). Data obtained with these methods will help refine productivity estimates, identify areas of physiological stress caused by low nutrients and locate transitions in the species composition of phytoplankton communities.

The quality of satellite ocean-color measurements continues to improve with each generation of sensors and with refinements in processing and analysis techniques. New products and capabilities are anticipated within the next few years (Yoder, 2000). For example, data from the new MODIS sensor, which measures chlorophyll fluorescence as well as concentrations, should help investigators identify phytoplankton physiological conditions related to nutrient stress. This information should lead to improved calculations of basin-scale productivity.

Inverse bio-optical models are now able to separate CDOM from chlorophyll; in the future, they may be able to distinguish among types of phytoplankton. Of particular relevance to biogeochemical cycle studies is the possibility of using ocean-color sensors to locate and map regions containing high abundances of nitrogen-fixing phytoplankton such as *Trichodesmium* (see Michaels et al., this issue). Numerical modelers will learn how to assimilate new data from satellite-mounted sensors into coupled biogeochemical-physical models to improve and extend their descriptive and predictive capabilities.

Finally, multiyear ocean-color data sets will help determine seasonal to interannual variability on ocean basin scales. Figure 5 shows the latitudinal progression of seasonal high chlorophyll concentration during 1998–2000 along the former NABE meridian of 20°W. Future carbon-cycle studies will use data sets of this sort to help focus *in situ* sampling from ships and moorings on key periods and locations as well as to achieve a better understanding of interannual variability.

Figure 6 shows chlorophyll *a* time-series measurements at two grid points in the South and North Atlantic. They contain some interesting features that illustrate how far satellite ocean-color observations have come since the CZCS era. First, a comparison of CZCS and SeaWiFS measurements at the South Atlantic grid point illustrates the improvement in Southern Ocean coverage between CZCS and SeaWiFS. Second, maximum and minimum chlorophyll *a* concentrations derived from POLDER, OCTS and SeaWiFS measurements are comparable, demonstrating that it will be possible to link measurements from different sensors to make decadal or longer data sets. Finally, both the CZCS and SeaWiFS data from the North Atlantic and the SeaWiFS data from the South Atlantic show interannual variability. They indicate that satellite ocean-color measurements may prove useful for determining the effects of climate and regime shifts on ocean productivity and may provide early warning of permanent changes to ocean ecosystems and biogeochemical cycles in response to human-induced climate perturbations.

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