Ocean Productivity – Climate Linkages Imprinted in Satellite Observations

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Ocean productivity and climate are intimately linked. Processes involved in this relationship can be observed using global satellite measurements of key ocean ecosystem properties. Analysis of satellite data reveals strong evidence of seasonal and El Niño Southern Oscillation influences on the distribution and magnitude of ocean photosynthesis and attests to the vital importance of sustained remote sensing observations. Limitations of the data, however, also emphasise the urgent need for advanced satellite sensor capabilities that will enable resolution of outstanding questions regarding the functioning of our Earth system.

IGBP has had an ongoing interest in ocean productivity, starting with its former JGOFS project (1988–2003) and continuing with its IMBER (2004–) and SOLAS (2003–) projects. This article explains how the examination of changes in ocean productivity can be surveyed through the development of new remote sensing methods.

Terrestrial plant photosynthesis greatly exceeds gross photosynthesis in the oceans, but this difference is roughly equivalent to the respiratory demands of the non-photosynthetic tissues in terrestrial plants (i.e., stems, roots). Consequently, annually-integrated net primary production (NPP), that fraction of newly formed organic material available for consumption by heterotrophic communities, or net accumulation of plant material, is of similar magnitude for Earth's land and oceans systems – of the order of 50 billion tons of carbon per year (Pg y^{-1}) [1,2]. The ubiquitous, free-floating, single-celled phytoplankton of the upper ocean are responsible for a vast majority of aquatic primary productivity.

Challenges and Solutions

Achieving an accurate estimate of global ocean NPP has been a notoriously difficult task (for a very nice review of estimates dating back to 1919 see [3]). One major issue is that the oceans are enormous and research ships travel only at about the speed of a bicycle. Thus, it is impossible for all practical purposes to assemble a globally representative ocean NPP data set by ship alone, much less the necessary temporal coverage to detect interannual trends. For ocean productivity modellers, therefore, the advent of satel-

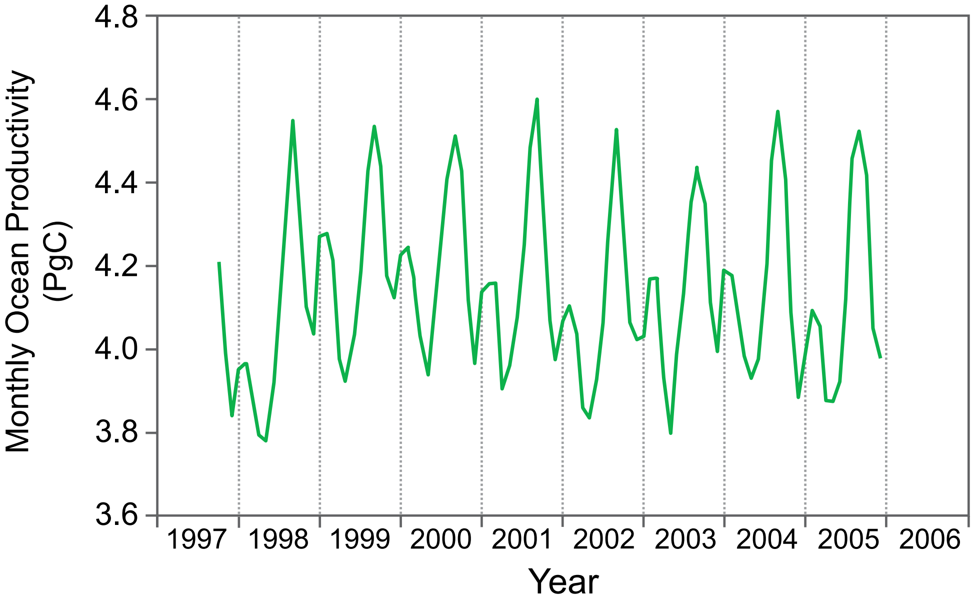

Figure 1. Monthly global ocean net primary production (NPP) between September 1997 and December 2005 based on SeaWiFS satellite data and illustrating the pronounced, repeated seasonal cycles. The strongest peak during each annual cycle corresponds to enhanced production in northern latitudes during the boreal summer. The peak each austral summer is notably lower, largely reflecting widespread iron limitation of phytoplankton growth in the Southern Ocean.

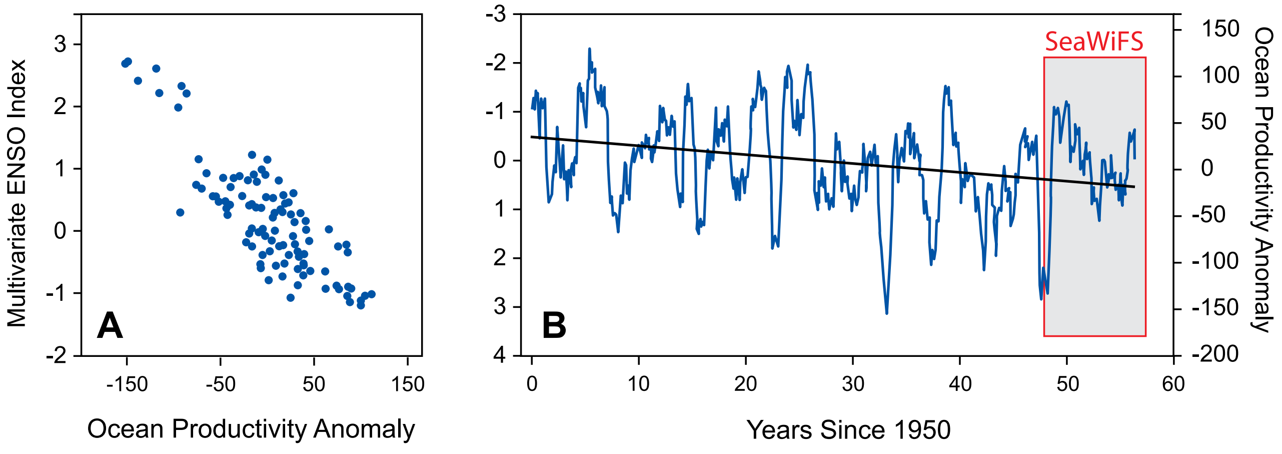

Figure 2. (A) Over the SeaWiFS record, ocean productivity in the global permanently stratified oceans varied with the strength of the ENSO cycle (assessed by the Multivariate ENSO Index, MEI). Monthly productivity anomalies represent deviations from the 'average' monthly value calculated for the 9-year record.

(B) MEI variability within the SeaWiFS era (red box) is within the range of variability observed since 1950 (left axis, note in this panel, MEI is low at the top and high at the bottom). Application of the relationship shown in (A) to the full MEI record may provide a sense of how ocean productivity varied over the same period (right axis; units = 10^{12} g C month^{-1}). Regression analysis of the full data set suggests a decreasing trend of 9 x 10^{12} g C per decade ($p < 0.001$).

lite global ocean colour sensors marked a true revolution. Presently, the high-quality ocean satellite data record extends back nearly a decade.

Conditions necessary to support phytoplankton net photosynthesis and growth exist only in the thin upper veneer of the ocean. This zone, referred to as the 'photic layer', is in intimate contact with the overlying atmosphere and exhibits particularly pronounced temporal variability. Environmentally-driven fluctuations in ocean NPP are dominated by the seasonal cycle (Figure 1), followed by influences of the El Niño Southern Oscillation (ENSO) cycle. Superimposed on these two higher-amplitude signals are the more subtle changes associated with basin-scale oscillations (e.g., the Pacific Decadal Oscillation) and longer-term climate trends. A decade's worth of satellite data is not sufficient to clearly resolve the impact of these later climate forcings, but it is sufficient to probe into the underlying climate-ocean biology relationships.

Phytoplankton Variability

While the satellite sensor Coastal Zone Color Scanner (CZCS: 1978–1985) provided the proof-of-concept that biologically relevant ocean data could be retrieved from space, it wasn't until the launch of the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) in 1997 that a science-quality ocean colour record truly began. Recently, we investigated the SeaWiFS record for quantitative links between global changes in ocean biology and fluctuations in climate [4].

Our analysis began by first removing the dominant seasonal cycle (Figure 1) from nine years of SeaWiFS-based chlorophyll and NPP estimates. We then compared the resultant chlorophyll- and NPP-anomalies to coincident changes in (i) the Multivariate ENSO Index (MEI) [5], (ii) a measure of surface stratification based on density differences between 10 and 200 meters, and (iii) spatial patterns in Sea Surface Temperature (SST) changes [4]. Our first finding was that global ocean NPP anomalies, and particularly anomalies in the permanently stratified oceans, were highly correlated with the MEI. Specifically, we found that tropical Pacific warming periods (i.e., higher MEI values) corresponded to net global decreases in NPP and chlorophyll, while cooling periods had the opposite effect (Figure 2A). When viewed in the context of the 50-year MEI record (Figure 2B, left axis), it is clear that fluctuations during the SeaWiFS era (red box in Figure 2B) are well within the normal range of ENSO variability for the past half century. We then compared global NPP anomalies with changes in stratification intensity and again found a very strong correspondence [4]. This result provides observational confirmation of a relationship between global stratification and NPP commonly featured in ocean circulation-ecosystem models [6] and long observed on local and regional scales. Finally, comparison of NPP and SST changes between 1999 and 2004 revealed a general inverse relationship that was stronger in the Pacific and Atlantic oceans than in the Indian Ocean [4]. This comparison illustrated well how overall net warming periods are actually composed of both warming and cooling events at the regional scale, with coherent impacts on NPP.

What Next?

NPP is not something that can be measured from space, but instead is derived from observed changes in ocean optical properties. Each step in this derivation adds uncertainty, so quantifying and reducing this uncertainty remains an on-going challenge. The temporal trends and spatial patterns in chlorophyll and NPP we describe [4] can be traced directly to changes in measured optical properties. The tight coupling between this variability and independent, coincident changes in surface stratification, the MEI, and SST lend confidence to the satellite results. But are there alternative ecosystem-level explanations for the observed patterns which are equally consistent with the climate indices? In fact there are, and resolving the significance of these represents another great challenge for future satellite ocean biology and biogeochemistry research.

The question is simply: "What ecosystem properties could have changed over the SeaWiFS record such that mixed layer light absorption decreases (i.e., the water gets clearer) when stratification increases?" Three potential answers come to mind: (i) a decrease in phytoplankton abundance due to reduced nutrient flux, (ii) a shift to higher carbon: chlorophyll ratios reflecting enhanced nutrient stress and/or elevated light levels with shallower mixing, and (iii) a reduction in light absorption by coloured dissolved organic material (cDOM) due to enhanced photobleaching. The first of these is consistent with changes in NPP. The second represents physiological adjustments to changing mixed layer growth conditions that may (due to nutrient stress) or may not (due to higher light levels) be associated with changes in NPP. The third does not necessitate a change in NPP.

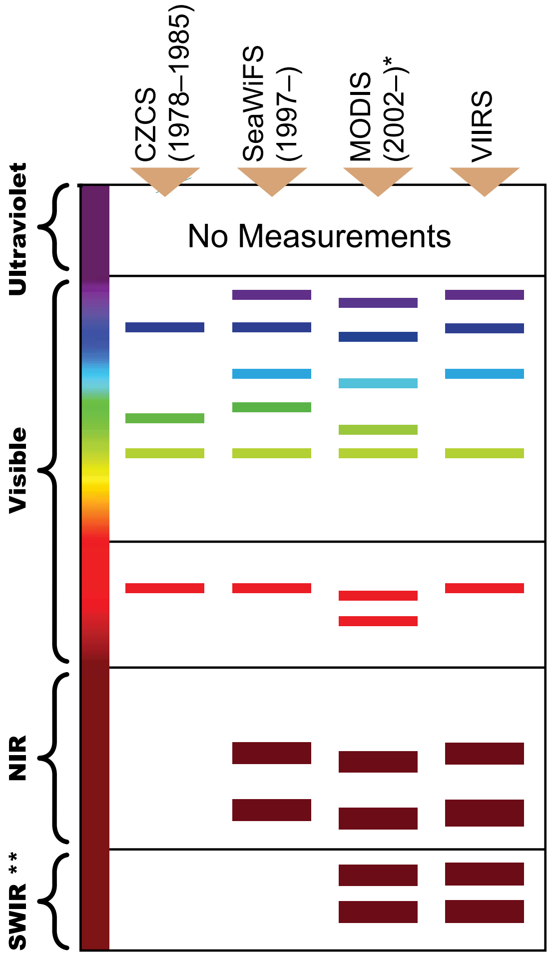

Figure 3. Measurement wavebands for the Coastal Zone Color Scanner (CZCS), Seaviewing Wide Field-of-view Sensor (SeaWiFS), and Moderate Resolution Imaging Spectroradiometer (MODIS) heritage ocean sensors and for the upcoming VIIRS sensor.

*Moderate Resolution Imaging Spectroradiometer (MODIS) on Terra was launched in 2000, but does not yet provide science quality ocean data.

**MODIS/Visible Infrared Imaging Radiometer Suite (VIIRS) SWIR band are not optimized for oceans.

Satellite Sensors Past, Present and Future

So which of the above interpretations is correct? Or did they all contribute? Are there yet other explanations for the SeaWiFS observations? Answers to these questions reside in our ability to accurately separate optically-active constituents (in other words, 'What's in the water and how much of it is there?').

From the first sensor, CZCS, to the upcoming Visible Infrared Imaging Radiometer Suite (VIIRS), the basic satellite ocean colour waveband set has changed very little (Figure 3). This measurement set traces to the conventional wisdom regarding ocean optics at the time when CZCS was designed, specifically that all light-absorbing components in the water column co-vary in a globally consistent manner with chlorophyll – a concept referred to as the '*bio-optical assumption*' [7,8,9]. This essential assumption underlies all waveband-ratio algorithms applied to, or planned for past, present, and future satellite data. However, in the decades since CZCS, it is has become abundantly clear that the bio-optical assumption is *incorrect*. We now understand that optically active ecosystems constituents do, in fact, exhibit significant independent behaviour [e.g., 9] and new spectral matching algorithms are being developed to accommodate this independence [e.g., 10,11]. The full potential of this powerful new approach, however, can not be realised with the heritage satellite waveband set (Figure 3).

The time is ripe for a new era in satellite observations enabling the maturation of global ocean biology and biogeochemistry research. Of foremost importance is an expansion of sensor capabilities allowing optical features of key ecosystem components and characteristics to be readily distinguished. Such measurements should provide regular global coverage of high spectral resolution (~5 nm resolution) data extending from the Near Infrared (NIR) down to the information-rich near-ultraviolet region (350–400 nm), and include specific Short Wave Infrared (SWIR) bands for atmospheric corrections over turbid coastal waters. Future sensor designs should also reflect 'lessons learned' from heritage missions, such as the importance of regular lunar observations and tilting capabilities to avoid data loss from sun glint, and include rigorous pre-launch sensor characterisation and post-launch field calibration and validation.

The SeaWiFS sensor has been a remarkable success story, but it has already entered its fifth lifetime extension and will, perhaps soon, come to an end. The follow-on MODIS (Moderate Resolution Imaging Spectroradiometer) sensor on EOS AQUA is likewise providing high-quality ocean colour data, but it too is now in its first lifetime extension. With these two sensors, the oceanography community has enjoyed a decade of high-quality ocean colour data, but we have erroneously come to expect that such data will continue into the future and be freely available to all. In truth, upcoming planned sensors are unlikely to provide ocean colour data of equivalent quality as SeaWiFS, and may not be launched in time for significant data overlap with SeaWiFS or MODIS. None of them provide the new measurements needed to resolve questions regarding the true nature of detected trends in global ocean properties. Given the long lead-time for launching a satellite (*minimum* 4 years), urgency is upon us to secure support for a new advanced sensor and begin its development.

SeaWiFS has given us a glimpse into climate-ocean biology interconnections of our Earth system and demonstrates the vital importance of sustained satellite measurements. But with what confidence can we forecast the relationships resolved? Does the correspondence between ocean NPP and the MEI (Figure 2A) allow a 50 year hindcast of NPP changes (Figure 2B, right axis) or was this relationship different before SeaWiFS? If the mechanisms have remained consistent, then what is driving the apparent 50-year downward trend in NPP of roughly 10^{13} g C decade^{-1} (Figure 2B, black line)? With so many unanswered questions remaining, now is certainly not the time for an interrupted or degraded data record, but rather a time to expand our global ocean observing capabilities as outlined in a recent community report for NASA's Ocean Biology and Biogeochemistry Program [12].

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