State of Climate 2011 - Global Ocean Phytoplankton

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Phytoplankton photosynthesis in the sun lit upper layer of the global ocean is the overwhelmingly dominant source of organic matter that fuels marine ecosystems. Phytoplankton contribute roughly half of the global (land and ocean) net primary production (NPP; gross photosynthesis minus plant respiration) and phytoplankton carbon fixation is the primary conduit through which atmospheric CO_2 concentrations interact with the ocean's carbon cycle. Phytoplankton productivity depends on the availability of sunlight, macronutrients (e.g., nitrogen, phosphorous), and micronutrients (e.g., iron), and thus is sensitive to climate-driven changes in the delivery of these resources to the euphotic zone.

From September 1997 until December 2010, a near-continuous record of global satellite ocean color observations was available from the Sea viewing Wide-Field of view Sensor (SeaWiFS) mission (e.g., McClain et al. 2004; McClain, 2009). Great efforts were made to insure the stability and accuracy of the SeaWiFS radiometric calibration enabling investigators to address relationships among ocean environmental conditions and phytoplankton productivity (e.g., Behrenfeld et al. 2006; McClain, 2009; Siegel et al. in review). The ecosystem property most often derived from ocean color data is surface chlorophyll concentration (Chl). Chl provides a measure of phytoplankton pigments and its variability reflects the combined influences of changes in phytoplankton biomass and its physiological responses to light and nutrient levels (e.g., Falkowski, 1984; Behrenfeld et al. 2005, 2008; Siegel et al. 2005; Siegel et al. in review). Figure 1 shows the SeaWiFS mission mean (Oct 1997 to Nov 2010) fields of Chl. Values of Chl span three orders of magnitude globally (0.03 to >30 mg m^{-3}) and its spatial patterns mimic large scale, climatological patterns in Ekman pumping and seasonal convective mixing (Sverdrup, 1955; Yoder et al. 1993). Higher values of Chl are found in regions of seasonal deep mixing (e.g., North Atlantic and in the Southern Ocean) and sustained vertical upwelling (e.g., Equatorial Atlantic and Pacific Oceans, off California and Peru coasts), while low values are found in the low-nutrient, permanently stratified central ocean gyres (Fig. 1).

Unfortunately the SeaWiFS ceased operating in December 2010 and assessments of global ocean phytoplankton for 2011 require other satellite data assets. Here we use observations from NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) on the Aqua platform and the European Space Agency's (ESA) Medium-Resolution Imaging Spectrometer (MERIS) instruments. Observations of chlorophyll concentration, using bio-optical algorithms similar to the SeaWiFS operational algorithms, were available from both sensor data sets and monthly binned imagery were available starting in July 2002 for both MODIS and MERIS. Raw data from the two satellite sensors are collected and processed by different groups, although many of the same field data and algorithms are employed for both (processing details are in the references listed in the caption for figure 2). Importantly, the methods and source data used to track temporal changes in the satellite calibrations are different for MODIS and MERIS (e.g., NRC, 2011).

Anomalies of $\log_e$(Chl) for the year 2011 for both MODIS and MERIS are shown in Figures 2a and 2b, respectively. Annual anomalies are calculated from monthly anomalies for each data set summed over the year 2011. Natural log transformations are commonly used to interpret data that vary over many orders of magnitude and $\log_e$(Chl) anomalies can be interpreted as the difference in Chl normalized by its mean value, or simply a percentage change (Campbell, 1995).

Both MODIS and MERIS chlorophyll values in 2011 show differences from the long-term mean that are greater than 40% in many areas (Figs. 2a and 2b). A good correspondence is found in the spatial locations of anomalous Chl values between the two data sets, although the MODIS Chl anomalies appear to be more negative overall. Both data sets find high values of Chl for 2011 throughout much of the tropical Pacific Ocean, subtropical North Atlantic Ocean, tropical Indian Ocean, and in portions of the Southern Ocean. Conspicuously low values of Chl during 2011 were found in the western Indian Ocean, the tropical Atlantic, and globally throughout the subtropics.

The climate state of 2011 can be characterized by the development of a strong La Nina event during the second half of the year and a strong negative Pacific Decadal Oscillation (Reference to other parts of the SoC report). In fact, the "wishbone" shaped feature indicative of a La Nina transition can be seen in the log-transformed Chl distribution across the tropical Pacific (Figs. 2a and 2b). The 2011 SST anomaly (SSTA; Fig. 2c) is indicative of a reemergence of La Nina conditions, strengthening of negative PDO, development of a positive Indian Ocean Dipole, and above-normal SST values in the tropical N. Atlantic and mid-latitude southern oceans (Xue et al. this report). These patterns in SSTA imprint generally inverse signals in the Chl anomalies (compare Figs. 2a & 2b with Fig. 2c). However the expected inverse relationship is not perfect and high / low Chl anomalies are found where the SSTA signals are mixed, such as in the tropical Indian Ocean.

To place the year 2011 in a broader climatological context, we compare monthly anomalies of $\log_e$(Chl) averaged over (Fig. 3a) the cool region of the northern hemisphere (NH) oceans (mean SST < 15°C), (Fig. 3b) the warm ocean (mean SST > 15°C), and (Fig. 3c) the cool region of the southern hemisphere (SH) oceans (Fig. 1 shows the location of the mean 15°C isotherm) for the SeaWiFS (red), MODIS (blue) and MERIS (green) data records. Anomalies are calculated as the difference in monthly log-transformed chlorophyll determinations for each 1° bin from the respective mission's climatology and then summed over the three regions of interest. As before, the natural log-transformed anomalies can be interpreted as percent differences from normal conditions. This evaluation of long-term temporal anomalies follows procedures from previous State of Climate reports and other publications (e.g., Behrenfeld et al. 2006; 2009; O'Malley et al. 2010; Siegel et al. 2011; in review).

For the most part, aggregate Chl anomalies are bounded approximately by ±10% differences from normal conditions for the cool ocean aggregates (Figs. 3a and 3c) and roughly ±4% for the warm oceans (Fig. 3b). Conspicuous outliers are found for the MERIS mission early in the record (particularly for the cool ocean aggregates) and for the MODIS record in late 2011. Sampling is likely to have an important role in the dispersion of results for the high latitude aggregates during the winter because high solar zenith angles greatly reduce the extent of the regions where good ocean color assessments can be made. The MODIS record for the last part of 2011 is 15% to about 30% lower than normal conditions, depending on the ocean region. This extreme result is neither expected nor supported by the MERIS data record, which instead shows positive Chl anomalies in late 2011 for the warm ocean (Fig. 3b).

The disparity among satellite data records illustrated in figure 3, especially for 2011, clearly challenges our ability to distinguish global ocean ecosystem changes over interannual time scales. While the global aggregate time series (Fig. 3) shows only a fair correspondence between missions, the spatial patterns for 2011 anomalies look broadly similar for MODIS and MERIS (Figs. 2a and 2b, respectively). The calculation of the global aggregates averages over many regional-scale anomaly features, creating a time series where smaller, persistent biases become apparent. This means that details in satellite sensor performance, data processing, and tracing of radiometric standards are very important when global aggregates are created and long-term trends are interpreted (e.g., Antoine et al. 2005; Siegel and Franz, 2010; NRC, 2011; Siegel et al. in review).

The SeaWiFS data record made extensive use of external standards (lunar views and intense ground efforts) to monitor changes in sensor gains and offsets over time and to set the sensor's absolute calibration (e.g., Franz et al. 2007; McClain et al. 2007; McClain, 2009). The relative uncertainty levels in lunar calibrations for SeaWiFS's top of the atmosphere reflectance determinations were ~0.1% (compared with the low-frequency fit relationship), making SeaWiFS the long-term standard against which other satellite ocean color records are compared (e.g., Franz et al. 2007; Eplee et al. 2011; NRC, 2011; Siegel et al. in review). The recent NRC report on "Sustained Ocean Color Observations" (NRC, 2011) made important recommendations from lessons learned from previous ocean color missions such as SeaWiFS. Central was the importance of assessing changes in radiometric calibration over time and the repeated reprocessing of these data streams.

Neither MODIS nor MERIS were designed to make monthly lunar views through the Earth viewing telescope that illuminates the complete optical path and all radiometric detectors (as SeaWiFS does). Consequently, other means have been employed to trace changes in sensor calibration over time (summarized in NRC, 2011). Briefly, MERIS relies on a dual solar diffuser approach where changes in the primary diffuser are monitored by a second diffuser that is infrequently exposed to sunlight (Rast and Bezy 1999; Delwart and Bourg 2011). The tracking of radiometric changes in MERIS is further complicated by the sensor design, which employs multiple cameras with multiple detectors per camera to span the cross-track view. Similarly, MODIS temporal calibration is complicated by the scanner design, which relies on a rotating scan mirror (rather than a rotating telescope) for cross-track observation and leads to different temporal changes at each scan angle. MODIS requires both a solar diffuser calibration and lunar observations to track changes in radiometric calibration (Xiong et al. 2010). However, these on-board measurements are insufficient to fully characterize the changes at all scan angles or to assess changes in polarization sensitivity (Franz et al. 2008) and additional calibration sources have been used to augment the on-board calibration system (Kwiatkowska et al. 2008; Meister et al. 2012). The MODIS Aqua data set presented here (version 2010.0) used SeaWiFS as a calibration source when it was available (Meister et al. 2012). The severe underestimates of Chl levels for 2011 shown in Fig. 3 are caused to large degree by the lack of SeaWiFS observations to cross-calibrate the MODIS sensor signals. Work is currently underway to use natural ground (cf., land) targets to correct the MODIS Aqua signals in the absence of SeaWiFS observations (B. Franz, pers. comm. February 2012). These are details, but the details are critical for assessing long-term changes in satellite ocean color observations – particularly at global scales.

In February of this year, the Visible Infrared Imaging Radiometer Suite (VIIRS) sensor on the Suomi NPP mission started acquiring science data. VIIRS's contribution to our understanding of changes in the global ocean biosphere demands careful attention and characterization of its radiometric changes over time and will require the successive reprocessing of the entire data stream (see specific VIIRS recommendations in NRC, 2011). The recent decision to acquire monthly lunar calibrations is an excellent step towards creating a climate quality data set from VIIRS. Similar requirements will also pertain to ocean color sensors on upcoming international missions, such as ESA's Ocean Land Colour Instrument (OLCI) and Japan Aerospace Exploration Agency's Second-Generation Global Imager (SGLI). The ability of these missions to extend the climate-quality ocean color time-series that started with SeaWiFS has yet to be determined, but establishment of temporal stability in the radiometric calibration will be a primary challenge. Finally, the Pre Aerosol Clouds and Ecosystem (PACE) mission is expected to have stringent requirements for tracking radiometric changes and one of its aims is to extend the climate quality observations started with SeaWiFS. The launch of the PACE mission is scheduled to occur no earlier than 2019.

The ecology and biogeochemistry of the oceans are constantly changing in response to climate variability and change. These changes of the ocean biosphere exhibit tremendous spatial heterogeneity that simply cannot be sampled adequately from point source or ship-based measurements (e.g., Siegel et al. in review). Viewing integrated global ocean responses is the province of satellite observations and, for the moment, our ability to visualize these changes is impaired. Regaining our full vision will require creative approaches for characterizing current space assets, continually reevaluating and reprocessing existing data sets, and focusing priorities of future sensors on the end-to-end mission requirements that ensure the retrieval of global, climate-quality data products over the lifetime of ocean sensor missions.

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Figure Captions:

Figure 1: Mean Chl distribution calculated over the entire SeaWiFS record from monthly level 3 imagery (November 1, 1997 to November 30, 2010) in units of log(mg Chl m^{-3}). Also shown is the location of the mean 15°C SST isotherm (black line).

Figure 2: Spatial distribution of summed monthly anomalies for 2011 for (a) MODIS $\log_e$(Chl) (units are % difference from climatology), (b) MERIS $\log_e$(Chl) (units are % difference from climatology) and (c) SST (units are °C). Anomalies are calculated on a 1 degree basis as differences in the year 2011 from monthly mean distribution over available data from each mission. MODIS observations are from Reprocessing 2010.0 (http://oceancolor.gsfc.nasa.gov/WIKI/OCReproc20100MA.html). MERIS observations are from its third data processing (http://earth.eo.esa.int/pcs/envisat/meris/documentation/meris_3rd_reproc/MERIS_3rd_Reprocessing_Changes.pdf). SST anomalies are based upon the Reynolds weekly SST version 2 (see Xue et al. this report for more details).

Figure 3: Monthly anomalies for $\log_e$(Chl) averaged over a) the cool region of the northern hemisphere (NH) oceans (mean SST < 15°C), b) the warm ocean (mean SST > 15°C) and c) the cool region of the southern hemisphere (SH) oceans for the SeaWiFS (red), MODIS (blue) and MERIS (green) data records. Figure 1 shows the location of the mean 15°C isotherm. Values are calculated from 1-degree gridded monthly log-transformed anomalies using each mission's climatology following procedures from previous State of Climate reports and other publications (e.g., Behrenfeld et al. 2006; 2009; O'Malley et al. 2010; Siegel et al. 2011; in review).