have the potential to provide a powerful constraint on the global estimates of ocean uptake and storage.


Photosynthesis by phytoplankton in the upper sunlit euphotic layer of the global ocean is the 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 CO₂ concentrations interact with the ocean’s organic carbon pools. Phytoplankton productivity depends on the availability of sunlight, macronutrients (e.g., nitrogen and phosphorous), and micronutrients (e.g., iron), and thus is sensitive to climate-driven changes in the delivery of these resources to the euphotic zone.

Since 1997, a near-continuous record of global satellite ocean color observations has been available from the Sea viewing Wide-Field of view Sensor (SeaWiFS; McClain 2009). SeaWiFS observations have enabled investigators to address the relationships among ocean environmental conditions and phytoplankton productivity. 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). Figure 3.36a shows the SeaWiFS mission mean (October 1997 to November 2010) fields of Chl. Values of Chl span three orders of magnitude globally (0.03 mg m⁻³ to greater than 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.

The SeaWiFS mission is the most consistent satellite ocean color data record ever collected (e.g., McClain 2009; NRC 2011). The entire SeaWiFS dataset has recently been reprocessed and its performance has been rigorously validated against at-sea observations (http://oceancolor.gsfc.nasa.gov/WIKI/OCReproc20100SW.html and links therein). Figure 3.36b shows the natural log (ln)-transformed Chl anomalies for the year 2010. These are calculated as the difference between monthly data for 2010 and the long-term monthly climatology and are averaged over the year 2010. Log transformations are commonly used to interpret data that vary over many orders of magnitude, and differences in ln (Chl) can be interpreted as the difference in Chl normalized by its mean value, or simply a percentage change (Campbell 1995; Boyce et al. 2010). Annual means are calculated as the composite of monthly anomalies of ln(Chl) from December 2009 through the end of November 2010 as the SeaWiFS mission ended on 14 December 2010 (http://oceancolor.gsfc.nasa.gov/forum/oceancolor/topic_show.pl?tid=3897).

Satellite chlorophyll values in 2010 show differences from the long-term mean greater than 40% in many areas (Fig. 3.36b). High Chl anomalies during 2010 occur east of Greenland, in the western equatorial Pacific, and throughout the Southern Ocean south of 55°S. Conspicuously low values of Chl during 2010 were found in the western Indian Ocean, north of Iceland, and in the eastern Atlantic off North Africa. Sea surface temperature variations for the year 2010 (Fig. 3.36c) can be characterized by: (1) a transition from El Niño to La Niña conditions during the summer 2010; (2) the development of a negative Pacific Decadal Oscillation pattern in the North Pacific during the fall/winter of 2010; and (3)
the development of a tripole SST anomaly pattern in the North Atlantic (as explained in section 3b). As seen by Behrenfeld et al. (2006), increased values of Chl generally correspond to reduced SST (and vice versa), supporting the importance of physical processes regulating global chlorophyll concentrations where changes in SST are a proxy for light, nutrient availability, and other forcing factors. In particular, a horseshoe-shaped positive Chl anomaly is observed centered on the western equatorial Pacific Ocean, indicative of an El Niño to La Niña transition (Fig. 3.36b).

The development of a tripole SST anomaly pattern in the North Atlantic (as explained in section 3b). As seen by Behrenfeld et al. (2006), increased values of Chl generally correspond to reduced SST (and vice versa), supporting the importance of physical processes regulating global chlorophyll concentrations where changes in SST are a proxy for light, nutrient availability, and other forcing factors. In particular, a horseshoe-shaped positive Chl anomaly is observed centered on the western equatorial Pacific Ocean, indicative of an El Niño to La Niña transition (Fig. 3.36b).

The processing of SeaWiFS data makes extensive use of external standards (lunar views and intense ground efforts) to set sensor gains and offsets, and advanced algorithms to correct satellite signals for the atmospheric path radiance and establish the relationships between ocean reflectance spectra and ocean properties (McClain 2009; Ahmad et al. 2010; NRC 2011). This enables one to assess changes in Chl over its 14 years of operation. Figure 3.37 shows standardized monthly anomalies for ln(Chl) and SST aggregated 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. (Figure 3.36a shows the location of the mean 15°C isotherm.) The sign of the SST standardized anomalies in Fig. 3.37 is flipped to accentuate the correspondence between ln(Chl) and negative SST (−SST). Broad correspondence is observed between ln(Chl) and −SST for the three regions although the only statistically significant (95% confidence interval) correlations are found for the warm ocean region where the mean SST is greater than 15°C ($R^2 = 0.19$; $p = 0.00$). An interesting feature is that the ln(Chl) and −SST anomalies appear to be coherent at low frequencies [i.e., decreases in SST correspond to increases in ln(Chl)], while on higher frequencies (many months to a few years) the cool SH region shows an inverse correlation [i.e., increases in SST correspond to increases in ln(Chl)].

A statistically significant decreasing time trend for ln(Chl) over the length of the SeaWiFS mission is found for the warm ocean region (trend = −0.19% yr⁻¹; $p = 0.01$; Fig. 3.37b), which corresponds to a significant increasing trend in SST (trend = 0.014°C yr⁻¹; $p = 0.00$). The opposing signs of these trends are consistent with ideas of a warming ocean reducing nutrient supply to the upper layers, thereby reducing phytoplankton pigment biomass (e.g., Behrenfeld et al. 2006). Significant trends are also found for the cool SH oceans (Fig. 3.37c), but in the opposite direction compared with the warm ocean. The cool SH oceans show increasing anomalies in ln(Chl) over time (0.82% yr⁻¹; $p = 0.00$) and a cooling trend in the SST (−0.024°C yr⁻¹; $p = 0.00$). Significant time trends in ln(Chl) and SST anomalies are not found for the cool NH ocean (Fig. 3.37a).

The regional time trends presented here from the SeaWiFS mission are inconsistent with a recent analysis of centennial-scale Secchi disk and chlorophyll determinations made by Boyce et al. (2010). Boyce and his coauthors show global chlorophyll
levels decreasing over the past century at a rate nearly equal to 1% per year (as well as decreasing trends for six of eight regions in their analysis). For the warm ocean, the present trends from SeaWiFS (Fig. 3.37b) are roughly one-fifth of the centennial trends found by Boyce et al. (2010); while for the cool SH ocean, a trend of increasing chlorophyll concentrations is observed (Fig. 3.37c). Obviously, these two ocean Chl trend estimates are not evaluating the same period of time and work is needed to connect these two datasets to make a consistent long-term estimate of change in phytoplankton chlorophyll levels.

The time trends of ln(Chl) and SST are shown on local scales in Fig. 3.38. The correlation coefficient between local anomalies in ln(Chl) and SST is shown in Fig. 3.38a where significantly (95% confidence interval) positive correlations are in red and negative correlations in blue. Sites with insignificant correlation are plotted in gray. The dominant pattern here is the large degree of significant inverse correlation between local-scale ln(Chl) and SST anomalies throughout the warm ocean. Positive local-scale correlations are also found in the cool NH and SH Atlantic Ocean and for the Bering Sea.

**Fig. 3.37.** Time series of standardized ln(Chl) (green) and negative SST (blue) monthly anomalies for (a) ocean regions of the Northern Hemisphere where the mean SST < 15°C, (b) the warm ocean where mean SST values are greater than 15°C, and (c) regions of the Southern Hemisphere where the mean SST < 15°C. Anomalies are plotted in standardized form (unit variance and zero mean). SST time series are created from optimally merging MODIS Aqua/Terra SST4 and AVHRR Pathfinder products on 1° bins and monthly anomalies are summed over the three regions.

**Fig. 3.38.** (a) Spatial distribution of the local-scale correlation coefficient (R) between ln(Chl) and SST, (b) local-scale time trends in ln(Chl) anomalies (in % yr⁻¹), and (c) local-scale time trends in SST anomalies (in °C yr⁻¹). Only significant (95% confidence interval) correlations and trends are plotted. Calculations are made over the entire SeaWiFS record (Oct 1997–Dec 2010) and on a local-scale 1° bin in latitude and longitude. Also shown in (a) is the 15°C SST isotherm (black line).
Spatial patterns in local-scale time trends can also be examined. Local-scale trends in ln(Chl) and SST anomalies are shown in Figs. 3.38b and 3.38c, respectively. Here, regions of significantly decreasing Chl values are found throughout the warm oceans and in particular in the tropical Atlantic Ocean (Fig. 3.38b). Values of increasing Chl are found in the southern Atlantic and Pacific Oceans, the tropical Pacific, and for the eastern boundary currents of the Pacific Ocean. Local-scale SST anomaly trends show interesting patterns with significantly increasing SST within the major subtropical gyres and decreasing SST within the Southern Ocean, in the eastern Pacific, and the Gulf of Alaska (Fig. 3.38c). Clearly, the aggregated trends shown in Fig. 3.37 have many local-scale nuances and demonstrate the importance of global observations for assessing long-time changes in the oceans.

This section has focused on addressing changes seen from the SeaWiFS climate data record. The loss of this satellite, and hence the data record, creates a huge hole in observing capability and leaves open the question of how to bridge existing satellite datasets to make consistent long-term records of ocean biological properties (Siegel and Franz 2010; NRC 2011). Both NASA’s MODIS Aqua and ESA’s MERIS sensors are global missions and are operating well; fortunately, similar patterns in Chl are seen with MODIS Aqua observations. However, SeaWiFS data were an important part of the calibrations for MODIS Aqua (see http://oceancolor.gsfc.nasa.gov/REPROCESSING/R2009/modisa_calibration) and MERIS is now being reprocessed and going through a vicarious calibration with ground data. At this point, the continuation of the climate data record initiated by SeaWiFS is not fully guaranteed as current sensors are aging and issues exist with its identified successors (e.g., NRC 2011).