One area of new research in ocean acidification is linking ocean acidification with low oxygen (hypoxic) events along the continental shelves. Oxygen-poor environments present physiological challenges for marine organisms and these are also expected to increase in prevalence under anthropogenic climate change as a result of surface ocean warming and increased stratification (Bopp et al. 2002; Matear and Hirst 2003; Stramma et al. 2008; Rykaczewski and Dunne 2010). The term "hypoxia" implies levels of oxygenation under which macrofauna are negatively impacted. Conditions ranging from hypoxic (< 65 µM) to anoxic (0 µM) have been observed in near-bottom waters on the inner continental shelf within the California Current System with an apparent increase in the frequency and intensity of the oxygen deficit since 2000 (Chan et al. 2008; Grantham et al. 2004; Hales et al. 2006). The conditions of corrosivity and hypoxia are linked on a process level because when remineralization of organic matter occurs under oxic conditions, oxygen is consumed approximately in stoichiometric equivalence (170:117) with the production of CO_2. Processes that create aquatic oxygen deficits can also exacerbate the formation of corrosive conditions for calcareous organisms. Thus, globally there may be connections between regional hypoxia and ocean acidification on a global scale.

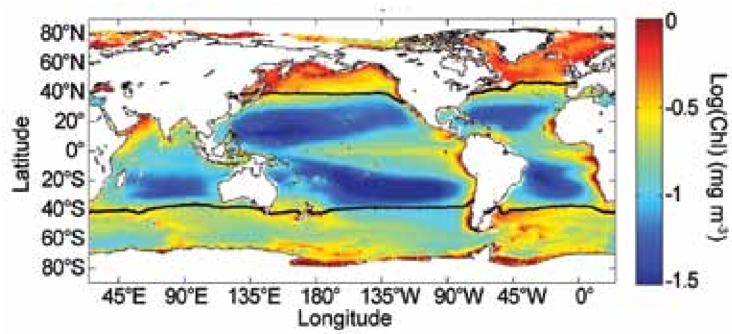

FIG. 3.36. Mean Chl distribution calculated over the entire SeaWiFS record from monthly level 3 imagery (1 Nov 1997 to 30 Nov 2010) in units of log(mg Chl m-^{3}). Also shown is the location of the mean 15°C SST isotherm (black line).

4. Global Ocean Phytoplankton—D. A. Siegel, D. Antoine, M. J. Behrenfeld, O. H. Fanton d'Andon, E. Fields, B. A. Franz, P. Goryl, S. Maritorena, C. R. McClain, M. Wang, and J. A. Yoder

Phytoplankton photosynthesis in the sunlit 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. 2012, manuscript submitted to *Remote Sens. Environ.*). 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. 2012, manuscript submitted to *Remote Sens. Environ.*). Figure 3.36 shows the SeaWiFS mission mean (November 1997–November 2010) fields of Chl. Values of Chl span three orders of magnitude globally (0.03 mg m^{-3} to > 30 mg m^{-3}) and their 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 Southern Oceans) 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. 3.36).

Unfortunately, the SeaWiFS ceased operating in December 2010 and assessments of global ocean phytoplankton for 2011 require other satellite data assets. Here, 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[1] are used. Observations of chlorophyll concentration, using bio-optical algorithms similar to the SeaWiFS operational algorithms, were available from both sensor datasets and monthly binned imagery 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 Fig. 3.37). Consequentially, 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 Figs. 3.37a and b, respectively. Annual anomalies were 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. 3.37a,b). A good correspondence is found in the spatial locations of anomalous Chl values between the two datasets, although the MODIS Chl anomalies appear to be more negative overall. Both datasets 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 Niña event during the second half of the year and a strong negative Pacific decadal oscillation (PDO; see section 3b). In fact, the "wishbone" shaped feature indicative of a La Niña transition can be seen in the log-transformed Chl distribution across the tropical Pacific (Figs. 3.37a,b). The 2011 SST anomaly (SSTA; Fig. 3.37c) is indicative of a reemergence of La Niña conditions, strengthening of negative PDO, development of a positive Indian Ocean dipole, and above-normal SST values in the tropical North Atlantic and midlatitude southern oceans (see section 3b). These patterns in SSTA imprint generally inverse signals in the Chl anomalies (compare Figs. 3.37a,b with Fig. 3.37c). 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.

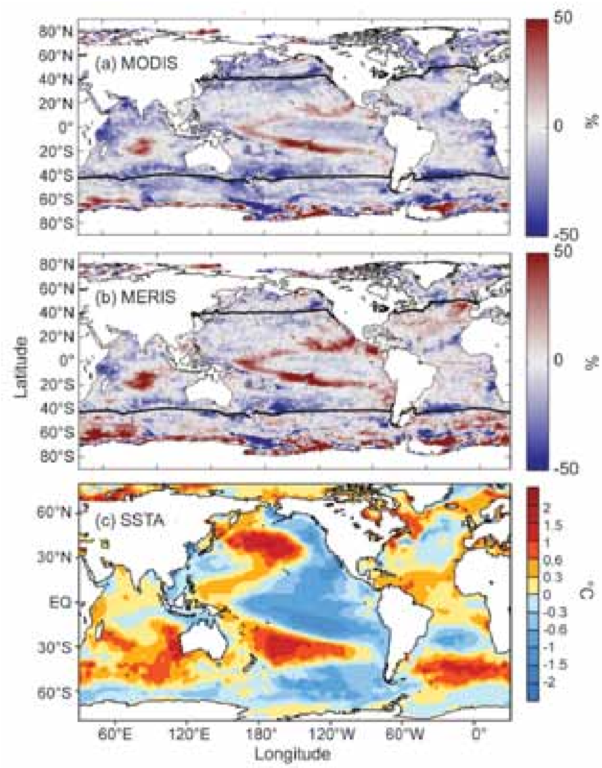

FIGURE 3.37.: Spatial distribution of summed monthly anomalies for 2011 for (a) MODIS loge(Chl) (% difference from climatology), (b) MERIS loge(Chl) (units are % difference from climatology) and (c) SST (°C). Anomalies are calculated on a 1 degree basis as differences in the year 2011 from monthly mean 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.

To place the year 2011 in a broader climatological context monthly anomalies of $\log_e$(Chl) averaged over the cool region of the northern hemisphere (NH) oceans (Fig. 3.38a, mean SST < 15°C), the warm ocean (Fig. 3.38b, mean SST > 15°C), and the cool region of the southern hemisphere (SH) oceans (Fig. 3.38c) for the SeaWiFS (red), MODIS (blue) and MERIS (green) data records are compared. (The black line in Fig.

1 Note communication with the Envisat satellite (which hosts MERIS) ceased on April 8, 2012. This will likely end the MERIS satellite ocean color record presented here (see http://www.esa.int/esaCP/SEMQ2EHWP0H_index_0.html for further details).

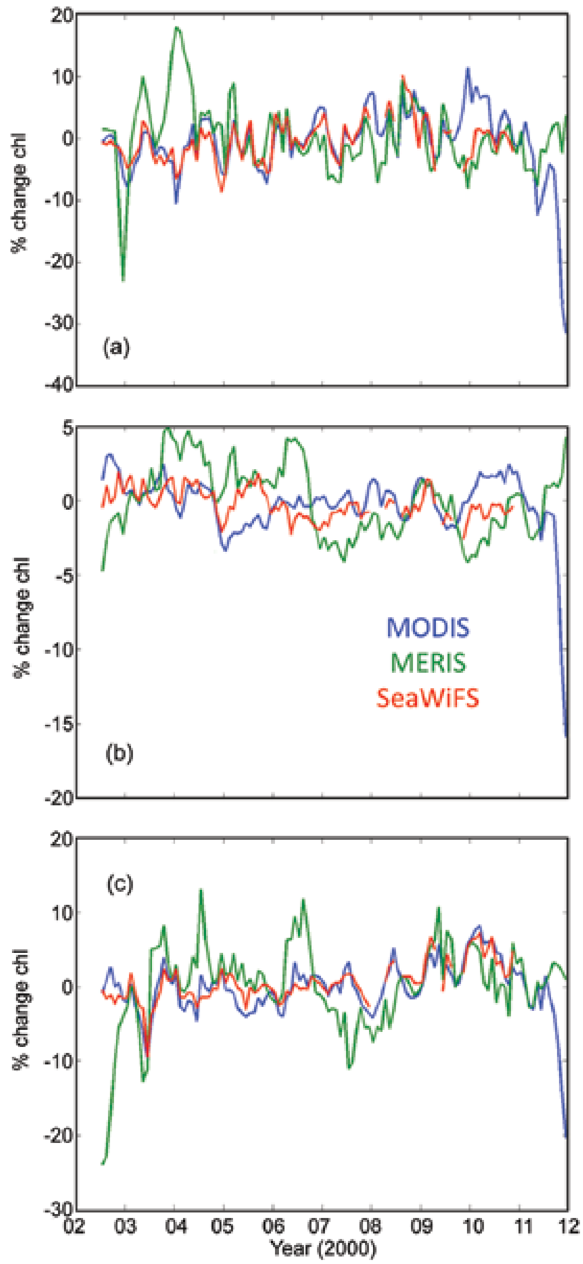

FIG. 3.38. Monthly anomalies for loge(Chl) averaged over (a) the cool region of the Northern Hemisphere (NH) oceans (mean SST < 15°C), (b) the warm ocean (mean SST > 15°C), and (c) the cool region of the Southern Hemisphere (SH) oceans for the SeaWiFS (red), MODIS (blue) and MERIS (green) data records.

3.36 shows the location of the mean 15°C isotherm.) 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 the Climate* reports and other publications (e.g., Behrenfeld et al. 2006, 2009; O'Malley et al. 2010; Siegel et al. 2012, manuscript submitted to *Remote Sens. Environ*.).

For the most part, aggregate Chl anomalies are bounded approximately by ±10% differences from normal conditions for the cool oceans (Figs. 3.38a,c) and roughly ±4% for the warm oceans (Fig. 3.38b). 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. 3.38b).

The disparity among satellite data records illustrated in Fig. 3.36, especially for 2011, clearly challenges the ability to distinguish global ocean ecosystem changes over interannual time scales. While the global aggregate time series (Fig. 3.38) shows only a fair correspondence between missions, the spatial patterns for 2011 anomalies look broadly similar for MODIS and MERIS (Figs. 3.37a,b). 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. 2012, manuscript submitted to *Remote Sens. Environ*.).

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 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. 2012, manuscript submitted to *Remote Sens. Environ.*). The recent *Sustained Ocean Color Observations* report (NRC 2011) made important recommendations based on lessons learned from previous ocean color missions such as SeaWiFS. Several recommendations from the report highlighted the importance of assessing changes in radiometric calibration over time and the repeated reprocessing of these data streams (NRC 2011).

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 dataset 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. 3.38 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 (land) targets to correct the MODIS Aqua signals in the absence of SeaWiFS observations (B. Franz 2012, personal communication). These are details, but the details are critical for assessing long-term changes in satellite ocean color observations—particularly at global scales.

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 cannot be sampled adequately from point-source or ship-based measurements Viewing integrated global ocean responses is the province of satellite observations and, for the moment, our ability to visualize these changes is impaired. Regaining full vision will require creative approaches for characterizing current space assets, continually reevaluating and reprocessing existing datasets, 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.