Chapter 10

Ocean Colour and Climate Change

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The longest currently-operating ocean-colour sensor (SeaWiFS) was launched in 1997, so it is not possible to detect decade-scale variability using SeaWiFS data alone. Newer and overlapping missions such as MODIS-Aqua and MERIS (launched in 2002) will hopefully ensure unbroken observations and provide global ocean-colour products up to 2012, with an increased spatial coverage. In the meantime, long-term changes can be observed by comparing climatological SeaWiFS/ MODIS/ MERIS data against data from the Coastal Zone Colour Scanner (CZCS), which operated between 1979 and 1985. The following section focuses on a few recent applications using these ocean-colour time-series to detect long-term trends in marine biology due to climate change. Notwithstanding the current limitation of ocean colour in obtaining a data set with a time frame of several decades, ocean colour is identified as an Essential Climate Variable (ECV) within the Global Climate Observing System (GCOS) action plan to support the United Nations Framework Convention on Climate Change (UNFCCC) and the work carried out by the Intergovernmental Panel on Climate Change (IPCC), representing a unique synoptic-scale view of the pelagic ecosystem. As such, it is absolutely essential to avoid any temporal gaps in the ocean-colour record, which has already suffered considerably from the ~10-year gap between the CZCS and SeaWiFS missions. Moreover, the provision of a single and consistent data stream of ocean-colour products from multi-platform devices would optimize the use of ocean colour-radiometry (OCR) data in climate research.

10.1 Long-Term Changes in Phytoplankton Biomass

Gregg *et al.* (2002) and Antoine *et al.* (2005) conducted a comprehensive re-analysis of CZCS data using similar methods and algorithms (as far as possible) to those used for current sensors, such that comparison of ocean-colour data sets from both eras could be achieved with a reasonable level of confidence. This analysis of decadal changes between CZCS and SeaWiFS data sets yielded an overall increase of 22% in the global ocean chlorophyll concentration (Antoine *et al.* 2005). Using only 6 years of SeaWiFS data, Gregg *et al.* (2005) also observed a slight increase in global ocean chlorophyll concentration (4.1%).

Although the global average ocean chlorophyll concentration is observed to be increasing, some regions of the ocean show a decrease. For the oceanic carbon cycle and ecosystem assessment it is important to understand where these changes are occurring. The largest positive changes between CZCS and SeaWiFS data sets are observed in the inter-tropical regions, whereas the oligotrophic gyres are becoming even more impoverished (Antoine *et al.*, 2005). Using a 9-year time series of SeaWiFS data, Polovina *et al.* (2008) demonstrated that in the North and South Pacific and North and South Atlantic, outside the equatorial zone, areas of low surface chlorophyll waters have expanded at average annual rates from 0.8 to 4.3% yr^{-1}. According to the authors, the expansion of low chlorophyll waters is consistent with global warming scenarios, implying increased vertical stratification in the mid-latitudes. The rates of expansion as observed with satellite data, however, greatly exceeds recent model predictions. Vantrepotte and Mélin (2008, subm.) also reported a decline in chlorophyll concentrations in the subtropical gyres at rates ranging from 1 to 5% per year, based on a decade of SeaWiFS data (1997-2007, Fig. 10.1).

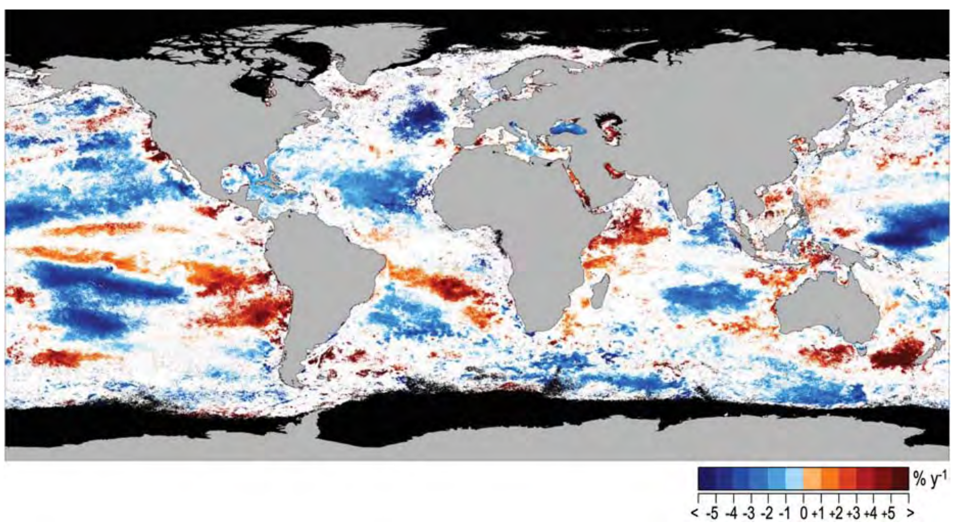

Figure 10.1 Linear changes in SeaWiFS-derived chlorophyll concentration from September 1997 to December 2007 (in % per year). Only the pixels for which a significant linear trend was detected, are reported ($p < 0.05$, Student-t test). (Image provided by Vincent Vantrepotte, Joint Research Centre, EC).

Positive changes, *i.e.* increases in chlorophyll concentrations, seem to be confined in coastal regions and upwelling areas. Several lines of evidence show an increasing strength of the seasonal upwelling in different systems over several decades, using other data sources (Bakun 1990; Snyder *et al.* 2003) and would explain the subsequent rise in chlorophyll in these regions. Likewise, using 11-years of data from SeaWiFs and its predecessor OCTS, Kahru and Mitchell (2008) found that bloom magnitudes have increased significantly in eastern boundary upwelling systems, as well as in a number of areas known to be sensitive to eutrophication (*e.g.* enclosed and semi-enclosed basins, outflow areas of large rivers). Some of the observed trends in bloom magnitude could be attributable to the strong El Niño of 1997-98 at the start of the time series. However, bloom magnitudes have increased in many areas even after this event.

Long-term changes in phytoplankton biomass could be reflected in the global ocean primary production and the entire carbon cycle. Comparing the CZCS record with 6 years of SeaWiFS data, Gregg *et al.* (2003) demonstrated a slight decrease of 6.3% in the global marine primary production, most of the decline being observed at mid- to high-latitudes. In contrast, low latitude and equatorial areas showed an increase in primary production between the CZCS and SeaWiFS eras. Using 9 years of SeaWiFS imagery (1997-2006), Behrenfeld *et al.* (2006) showed a decrease in net primary production over the years after an initial boost in 1998 due to the El Niño event.

Despite the different methodologies used, a certain level of consistency emerges from these OCR investigations, indicating that phytoplankton chlorophyll and primary production in large regions of the ocean (mid-latitude gyres) are decreasing over a multi-year period. Considering the limited ocean colour time-series being used (mainly SeaWiFS era), any interpretation of the changes as representative of longer term trends possibly linked to global warming would be speculative. Yoder and Kennelly (2003) documented a significant relationship between the inter-annual variability of chlorophyll and the large ENSO (El Niño Southern Oscillation) event which took place in 1997, and had global impacts for many years. Behrenfeld *et al.* (2006) also underline the striking correspondence between changes in primary production and a Multivariate ENSO Index, which would relate observed trends in chlorophyll and primary production to climate variability, rather than climate change.

10.2 Fisheries and Climate

The 1997/98 El Niño was one of the strongest ENSO events of the century. Ocean-colour satellite data, in synergy with data from an extensive array of moorings across the equatorial Pacific, have contributed enormously to our understanding of ENSO dynamics and their ecosystem impacts. Deepening of the thermocline, and cessation of upwelling along the equator and in the coastal ecosystems lowers ocean productivity and causes significant depression of the anchovy fisheries of Peru and Chile (Alamo and Bouchon, 1987; Escribano *et al.*, 2004). However, other species are positively impacted by El Niño, for example increases are observed in the biomass of sardine and mackerel (Bakun and Broad, 2003; Niquen and Bouchon, 2004). Satellite ocean-colour data have demonstrated that the effects of El Niño are not constrained to just the equatorial and coastal upwelling regions, but extend throughout most of the Pacific Ocean. For example during the 1997/98 event the Transitional Zone Chlorophyll Front (TZCF) was shifted ~5° south of its regular position (Bograd *et al.*, 2004), and lower chlorophyll values occurred across most of the subtropical Pacific (Wilson and Adamec, 2001).

On a longer time scale, the present wintertime position of the TZCF in the Pacific, as observed with SeaWiFS data set, is about 5° further north than it was during the CZCS time period (Fig. 10.2). This shift has also been seen in SST data used as a proxy for the TZCF (Bograd *et al.*, 2004). Data from the CZCS and SeaWiFS sensors have also been used to identify regions of the ocean which have experienced significant changes in the concentration of chlorophyll and rate of primary productivity in the past twenty years (Gregg and Conkright, 2002; Gregg *et al.*, 2003).

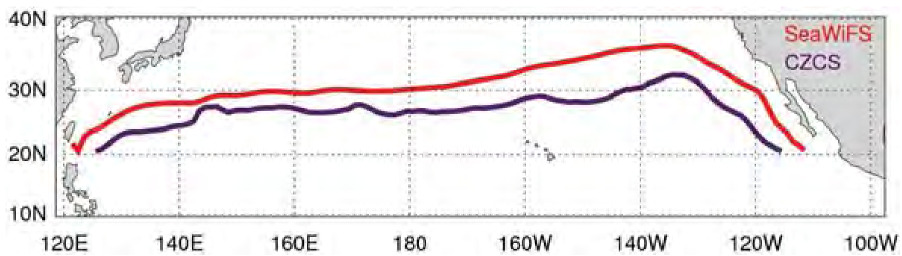

Figure 10.2 Interannual variation in the position of the TZCF indicated by the mean January position from CZCS data (1979-1985) in purple, and from SeaWiFS data (1998-2004) in red. The winter TZCF is presently ~5° further north from its position during the CZCS era. (Credit: Cara Wilson, unpublished data)

There is significant long-term temporal variability in fish stocks, and for over 150 years scientists have been trying to differentiate the effects of interannual variability, overfishing and long-term changes such as regime shifts, which are characterized by relatively rapid changes in the baseline abundances of both exploited and unexploited species (Polovina, 2005). Long-term variations in ecosystems often follow trends or patterns also observed in ocean and atmosphere properties (Mantua *et al.*, 1997; Hare and Mantua, 2000; Peterson and Schwing, 2003). For example, a shift in the North Pacific in the 1970's between a shrimp-dominated ecosystem to one populated primarily by several species of bottom-dwelling groundfish species coincided with a regional change from a cool to a warm climate (Botsford *et al.*, 1997; Anderson and Piatt, 1999; Fig. 10.3). Although similar phenomena have been seen for many different stocks, and in all ocean basins, the mechanisms that link large-scale ocean and atmosphere dynamics to changes in population abundances are not always clear (Botsford *et al.*, 1997; Baumann, 1998) and the relationships are not always constant over time (Solow, 2002). Ecosystem changes related to regime shifts are not in themselves harmful to the ecosystems as a whole (Bakun and Broad, 2003), but to maintain sustainability, management practices must be flexible enough to recognize and accommodate them (Polovina, 2005). Chassot *et al.* (2007) used satellite-derived primary productivity data together with catch data from European seas for the period 1998 to 2004, and found significant positive relationships between primary production and yield, suggesting a strong linkage between marine productivity and fisheries production. This is relevant in the context of climate change, because variations in primary production linked to global warming could strongly modify fisheries production in the future.

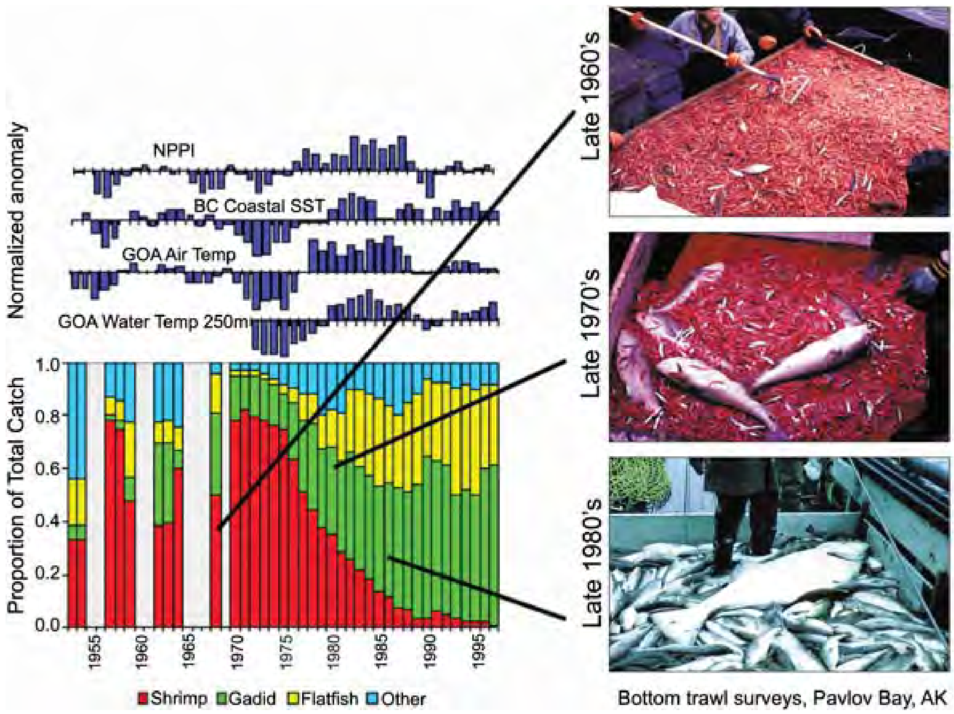

Figure 10.3 Changes in the composition of small-mesh trawl catches in the Gulf of Alaska (GOA) between 1953 and 1997, in relation to climate indices. Chart data expressed as normalized anomalies (NPPI: North Pacific Pressure Index; BC: British Columbia), and shown visually in photos of small-mesh bottom trawl surveys in Pavlov Bay, Alaska (right). Figures adapted from Anderson and Piatt (1999) and Botsford *et al.* (1997). Reprinted with permission from AAAS.

One of the current limitations of satellite data is the relatively short time-span of the data series. For fisheries applications it is crucial that climate-quality records of ocean colour be maintained so that existing satellite records will be able to serve as a benchmark against which to gauge future changes.

10.3 Toward a Long-Term and Consistent Ocean-Colour Time Series

To examine long-term changes in ocean colour for climate monitoring purposes, ocean-colour data sets need to be based on individual sensors with a significant historical archive, or a time-series of several overlapping, well-calibrated sensors that can be combined to produce a consistent, well-calibrated merged data set. Individual sensors typically have a nominal lifetime of 5 years, but in reality their operating period can be much shorter (*e.g.* OCTS which provided data for 8 months prior to a power failure), or longer (*e.g.* SeaWiFS currently in its 11^{th} year of activity). Currently, no operational satellite ocean-colour missions are designed to provide multi-decadal observations of the marine biological field, such as the NOAA-AVHRR series for measurement of sea surface temperature. However, ESA's Sentinel-3 series of operational satellites, the first of which is scheduled for launch in 2012, are designed to provide an uninterrupted flow of robust global data products. At the moment, the ocean-colour community has to rely on a number of individual missions launched by various space agencies, with radiometric sensors that differ in their technical specifications. Multiple overlapping missions, such as the current SeaWiFS, MODIS and MERIS missions, have the advantage of increasing the spatial coverage of the global ocean, which is more limited with a single sensor due to the effects of sun-glint and clouds (IOCCG 1999). The challenge is to maximize the information available by combining data from individual sensors, such that a reasonably consistent and well calibrated data stream of ocean-colour products can be generated independently of sensor characteristics and satellite orbital schemes.

NASA's Sensor Intercomparison for Marine Biological and Interdisciplinary Ocean Studies (SIMBIOS) Program was conceived in 1994 to examine the technical challenges of combining ocean-colour data from an array of individual missions to form consistent and accurate global bio-optical time-series products. A specific objective of the program was to develop appropriate methods for merging data from sensors with different viewing geometries, resolution (spectral, spatial and temporal), and other radiometric features. Several merged ocean-colour data sets have become available in recent years:

- NASA OBPG merged Chl-a data set based on SeaWiFS and MODIS-Aqua,
- NASA REASoN merged Chl-a, Colour Dissolved Material (CDM) and particulate backscattering (b_{bp}) data sets based on SeaWiFS and MODIS-Aqua,
- ESA DUE GlobColour multi-parameter (19 variables) data set based on SeaWiFS, MERIS and MODIS.

The merging of data from individual sensors not only provides a long time-series, but also increases the temporal coverage (see Table 10.1) and error characterisation of the final data set. The averaged daily coverage by individual sensors ranges from ~8% for MERIS to ~16% for SeaWiFS. The combination of two sensors increases the global ocean coverage to ~20-25% per day, and to ~30% per day with the combination of three sensors (IOCCG, 1999).

The GlobColour Project was initiated and funded by the ESA Data User Element (DUE) Programme in 2005 to develop a satellite-based ocean-colour data set to support global carbon-cycle research, and to satisfy the scientific requirement for a long time series of consistently calibrated global ocean-colour information with the

Table 10.1 Ocean-colour sensor average daily coverage plus standard deviation for 2003 (produced by Stephane Maritorena and based on the GlobColour Chl-a data).

Sensor(s)	Coverage (%)	Standard Deviation (%)
SeaWiFS	16.65	2.01
MODIS-Aqua	13.76	1.15
MERIS	8.51	1.48
SeaWiFS/MODIS-Aqua	24.22	1.94
SeaWiFS/MERIS	22.24	2.40
MODIS-Aqua/MERIS	19.92	1.74
SeaWiFS/MODIS-Aqua/MERIS	28.85	2.24

best possible spatial coverage. This was achieved by merging data from the SeaWiFS, MODIS-Aqua and MERIS missions. The project provides global daily, 8-day, and monthly merged data products at 4.6-km resolution for the time period 1997-2007, and is freely available to the scientific user community (`http://www.globcolour.info`).