The Ocean Colour Climate Change Initiative

Merging ocean colour observations seamlessly

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Remote sensing of the ocean has transformed many areas of marine science, by making visible complex flow patterns, and distributions of phytoplankton and sediment carried in surface waters. Ocean colour remote-sensing from space began in 1978, with the launch of NASA's Coastal Zone Color Scanner (CZCS) aboard the Nimbus 7 *satellite. Intended as a proof-of-concept, it was expected to operate for one year, but in fact remained in service until 1986. CZCS has been followed by sensors such as SeaWiFS, MERIS and MODIS which have increased the time-series of data available. So millions of pixels have been collected, but on any one day, areas of sea are obscured by cloud, dust or water in the atmosphere, and even 10 years' worth of images for a given month may have gaps. This problem can be addressed by combining data from several sensors, but is not straightforward. There may be systematic differences between sensors themselves, and further differences may be introduced through the application of algorithms to remove the influence of the atmosphere on a satellite sensor. Here, members of the Ocean Colour Climate Change Initiative (CCI) project team explain how work led by Plymouth Marine Laboratory, and funded by the European Space Agency, is tackling this challenge. Ed*

Ocean colour for climate studies

Ocean Colour CCI generates ocean colour products specifically designed for climate studies. The project runs in parallel with 12 others in the European Space Agency's (ESA's) CCI programme (http://www.esa-cci.org/), all of which are developing Essential Climate Variables (ECVs), i.e. key environmental variables that are economically and technically feasible to measure, and are useful for monitoring various components of the Earth system. The Ocean Colour CCI project aims to produce a long-term multi-sensor time-series of satellite ocean-colour data with specific information on errors and uncertainties; it is the only marine ECV targeting the biological field.

Ocean colour is influenced by many factors, including both suspended and dissolved components. However, it is largely determined by phytoplankton abundance, which can be indexed as chlorophyll concentration, and is a key factor in the ocean carbon cycle and hence important in all discussions dealing with pathways of carbon in the Earth System. Also, since phytoplankton are at the base of the pelagic food web, they are fundamental to understanding how the marine ecosystem responds to climate variability and climate change. Nevertheless, the role of phytoplankton and ocean colour in climate studies is still not fully understood, not least because other factors such as sediment load often complicate the picture.

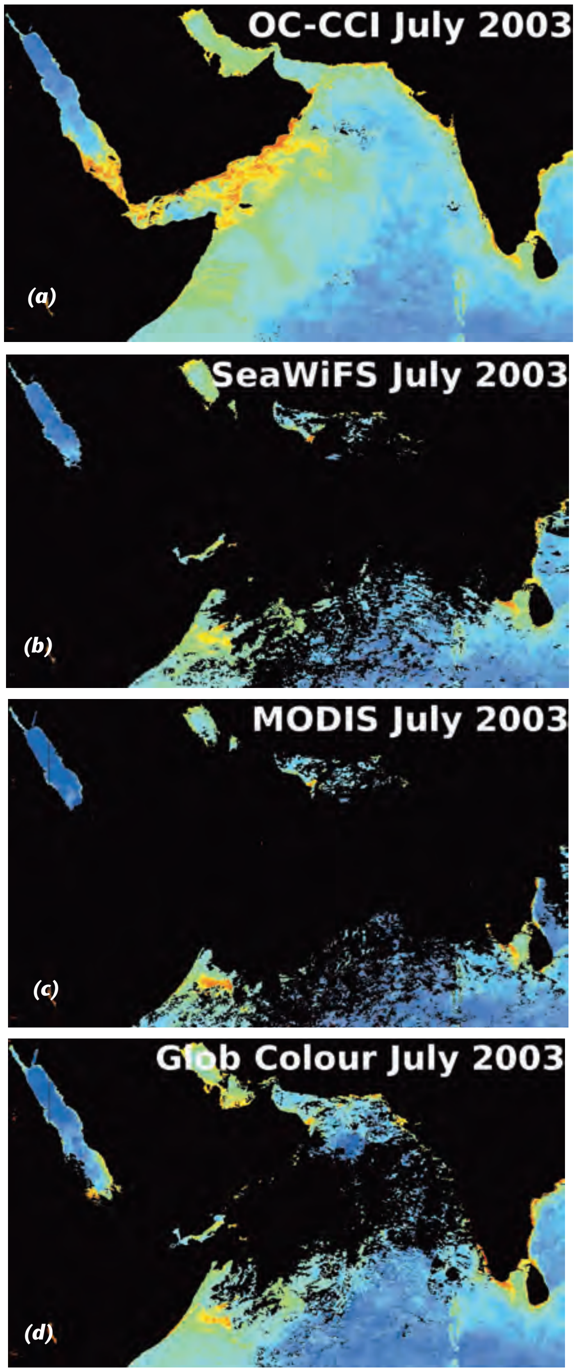


Figure 1 *Ocean colour images of the Arabian Sea/northern Indian Ocean, for July 2003, generated using:*
(a) *the ocean colour Essential Climate Variable, produced by the Ocean Colour CCI;*
(b) *SeaWiFS and* ***(c)*** *MODIS, the previous states of the art using unmerged data;*
(d) *the ESA GlobColour project, the previous state of the art using merged data.*

Ocean Colour CCI uses an improved atmospheric correction for the MERIS data and so can fill gaps that have previously existed in both single sensor and merged datasets. The image shows a marked improvement in coverage of the Arabian Sea, especially the region of high chlorophyll (red) resulting from coastal upwelling off Oman.

At the end of Phase 1, the project's activity had resulted in a 15-year merged ocean colour time-series of a quality that could reliably be used in climate change research. Phase 2, which started in 2014, aims to follow a cyclical update process with release of a revised dataset in 2015. Near-term updates included processing up to the end of 2014 (the current dataset extends until 2012) with longer term goals including the incorporation of data from future missions such as the EU Copernicus Ocean and Land Colour Instrument (OLCI) on board the *Sentinel-3* satellites.

Producing an ocean colour Essential Climate Variable has required a number of intermediate steps.

User requirements

User requirements underpin all Ocean Colour CCI activities; in Phase 1, a survey and consultation were undertaken at the beginning of the project, in order to incorporate the views of modellers and observational scientists alike. These results, along with requirements from the Global Climate Observing System (GCOS), form the design basis.

Ocean colour data products include remote-sensing reflectance in the visible domain, and derived chlorophyll concentration, in addition to a number of other optical properties computed from the radiances, including various inherent (absorption and scattering) optical properties of the upper ocean, and the diffuse attenuation coefficient for downwelling irradiance. They utilise data from ESA's MERIS and NASA's SeaWiFS and Aqua-MODIS archives.

Algorithm selection

The selection of algorithms is a key part of the development: firstly, to correct for atmospheric effects that mask the signal from the ocean (atmospheric correction); and secondly to convert the retrieved ocean-colour signal into biogeochemically relevant variables such as the chlorophyll-*a* concentration.

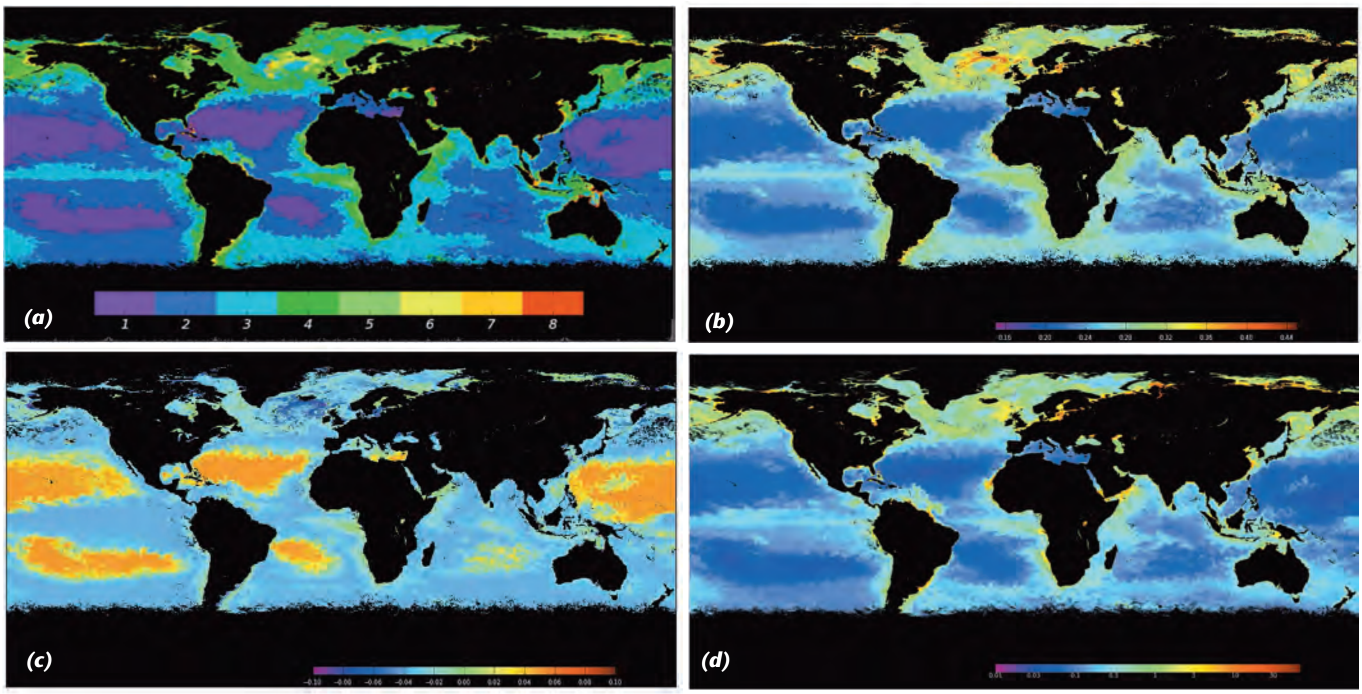
Many algorithms are available – each with its own limitations and advantages. To select the best one, a suite of algorithm-selection criteria was developed that includes qualitative considerations such as the robustness of the algorithms in the event of modifications in the marine ecosystem in a changing climate. The quantitative performance of the algorithms was also evaluated using a suite of statistical tests on satellite products matched with *in situ* observations. This process led to a significant improvement in the spatial coverage of data from the MERIS sensor (see Further Reading), as shown by its contribution to the Ocean Colour CCI image in Figure 1. The algorithm selection procedures have the potential to be routinely implemented, such that the performance of emerging algorithms can be compared with existing algorithms as they become available (see Further Reading).

Achieving climate-quality data

The Global Climate Observing System (GCOS) requirements identify time-series data of spectrally resolved remote-sensing reflectance and chlorophyll-*a* as a priority. However, since the three ocean colour sensors used in the project (SeaWiFS, MERIS and Aqua-MODIS) each had different sets of spectral bands, a reference sensor had to be selected and the remote-sensing reflectance wavebands of the other sensors shifted to that of the reference sensor (chosen to be SeaWiFS), ensuring a merged product at the same wavelengths throughout the time-series. This 'band-shifting' was also essential to determine inter-sensor biases, which had to be corrected, to avoid spurious trends in time-series data.

*There are various different ways of classifying ocean and coastal waters on the basis of their optical characteristics. For example, the terms Case 1/Case 2 are used when the dominant contributors are either chlorophyll-*a* (Case 1) or suspended inorganic sediment, detrital and dissolved material (Case 2). The system used in Figure 2(a) is based on the approach of Moore *et al.* (2009) (see Further Reading).

Figure 2 ***(a)*** *Example of a distribution of optical water classes* across the oceans for July 2003 (i.e. the class most commonly applicable during that month), ranging from clearest ocean water (class 1, purple) to waters that are highly productive and/or dominated by a high sediment load (class 8, red). These classications are used to assign corresponding uncertainties in chlorophyll-*a *generated on a pixel-by-pixel basis. These include* ***(b)*** *root-mean square difference error (log_{10}chl-*a*) and* ***(c)*** *bias values (log_{10}chl-*a*).* ***(d)*** *The resulting Ocean Colour CCI product for mean chlorophyll-*a* (mg m^{-3}) in July 2003. Note that root mean square difference errors are greatest (red) in highly productive areas and least in the low-nutrient centres of gyres, where bias values with reference to* in situ *data are highest.*



A major achievement for the project was devising a method to provide pixel-by-pixel error characterisation for the merged product. The uncertainties provided include root mean square error and bias, based on validation with *in situ* data (cf. Figure 2(b) and (c)). This was achieved through the use of optical classification of pixels (Figure 2(a)), and optical-class-based uncertainty characterisation. A number of optical water classes were defined by spectral reflectance values. Uncertainties were computed for each optical water class, for each product (see Box). The uncertainty for a product at any given pixel can then be estimated using the optical classification of the pixel and the class-specific product uncertainties.

A new integrated database of *in situ* observations was set up from a number of available sources such as MERMAID, NOMAD and SeaBASS, and matched up with satellite data to help establish the uncertainty characteristics. The database also provides the basis for the validation exercises; in addition, a number of comparison exercises have been undertaken to evaluate the consistency of the data products.

Version 1 of the Ocean Colour CCI dataset has provided improved coverage, error characterisation and bias correction, whilst meeting the GCOS requirements for temporal resolution and accuracy. Version 1 has recently been assessed by ocean colour and ecosystem modelling experts within the project, and their feedback is being taken into consideration for Version 3 of the product (see below).

Version 2 uses updated input datasets and extends the time-series to the end of 2013. It also optimises the uncertainty generation, incorporates an improved bias correction and improved MERIS cloud mask (the cloud mask removes any pixels that are not seawater, primarily cloud pixels). There have also been some minor changes to the format, and so scripts and code may need updating. Ongoing feedback is encouraged from all users; please email: help@esa-oceancolour-cci.org

The aim of Version 3 is to include new sensors, such as the NOAA/NASA Visible Infrared Imaging Radiometer Suite (VIIRS), to ensure long-term evolution of the ECV products while also focussing on reducing the uncertainties in Case 2 (primarily coastal) waters, which are high in sediment and/or dissolved organic material.

Ocean Colour Products

Spatial coverage: Global level 3 binned multi-sensor merged data as sinusoidal and geographic products at 4 km resolution
Temporal resolution: daily, 8-daily, monthly
Temporal coverage: 1997–2013 (Version 2); 1997–2012 (Version 1)

Main Ocean Colour products (ECVs)

Phytoplankton chlorophyll-*a* concentration (chlor_*a*) (mg m^{-3})
Remote-sensing reflectance (R_{rs}) at six wavelengths (sr^{-1})
Uncertainty layers are included

Other Ocean Colour products

Total absorption (a_{tot}) (m^{-1}) and **backscattering coefficients (b_{bp})** (m^{-1})
No uncertainty layers for either as a_{tot} is a combined product and there are insufficient data for b_{bp}

Phytoplankton absorption coefficient (a_{ph}) (m^{-1})
and **absorption coefficients for dissolved and detrital material (a_{dg})** (m^{-1})
Uncertainty layers are included

Diffuse attenuation coefficient for downwelling irradiance (K_d for light of wavelength 490 nm)
Uncertainty layers are included

Ocean Colour CCI products

The data can be directly downloaded via FTP (ftp://oc-cci-data:ELaiWai8ae@oceancolour.org/) or viewed/ downloaded via an interactive website at http://www.oceancolour.org/ which also includes a Composite Browser, Web GIS Portal and OPeNDAP access details. The tools for handling the data include plugin readers for BEAM and SeaDAS. For further details please consult the Product User Guide (http://www.esa-oceancolour-cci.org/?q=webfm_send/496) or website FAQ (http://www.esa-oceancolour-cci.org/?q=faq). A summary of the products is given in the Box above.

We gratefully acknowledge the support we have received from ESA, NASA and the community at large in developing the new merged time-series product.

All data products are freely available online, and all documentation is accessible on the project website (http://www.esa-oceancolour-cci.org/).

Further Reading

Brewin, R.J.W. and 24 others (2013) The Ocean Colour Climate Change Initiative: A round-robin comparison on in-water bio-optical algorithms, *Remote Sensing of Environment*. http://dx.doi.org/10.1016/j.rse.2013.09.016

Moore, T.S., J.W. Campbell and M.D. Dowell (2009) A class-based approach to characterizing and mapping the uncertainty of the MODIS ocean chlorophyll product. *Remote Sensing of Environment*, **113**, 2424–30.

Müller and 15 others (2015) A methodology for assessing atmospheric correction processors based on in-situ measurements, *Remote Sensing of Environment* (in press).

For more on ocean optics, including optical water classes, see the Ocean Optics Web Book http://www.oceanopticsbook.info/view/overview_of_optical_oceanography

More technical information can be found in a series of reports on the IOCCG website: http://www.ioccg.org/reports_ioccg.html

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