Colour, Climate, Carbon and Copernicus

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and many colleagues, including Carsten Brockmann, Andrei Chuprin, Tom Jackson, Dagmar Müller, Hajo Krasemann, Victor Martinez-Vicente, Mike Grant, Hayley Evers King, Andre Valente, Vanda Brotas, Steve Groom, Marco Zühlke, Nick Selmis, François Steinmetz, Didier Ramon…
Colour: where Light meets Life

Colour of the ocean tells us where and how the life-giving light is coupled to the ocean microflora. The more green the colour, the stronger the coupling.

It is the most fundamental phenomenon in the pelagic ecosystem: without it, the pelagic ocean would be sterile.

We can monitor this coupling through remote sensing. An ocean-colour image maps the strength of coupling between the ecosystem and its energy source.

Chlorophyll-a, a ubiquitous pigment contained in phytoplankton, is a major product.
As part of the larger Climate Change Initiative that deals with multiple Essential Climate Variables in the ocean, land, atmosphere and cryosphere, OC-CCI was charged with:

• Identifying user requirements
• Compare candidate algorithms and select suitable ones
• Establish uncertainties in products on a pixel-by-pixel basis
• Develop appropriate software for product generation
• Generate merged time series of ocean-colour products that meet user requirements
• Assess quality and validate products

Work carried out in collaboration with, and a lot of help from, NASA
Relevance and Applications of Products from Space & Perspectives from Models

CLEO Workshop was the last of a series of community consultations that guided OC-CCI work.

Some 160 participants
Band-shifting, bias correction, Merged, global, 4-km product

MERIS $R_{rs}(443)$

MODIS-A $R_{rs}(443)$

OC-CCI Merged, $R_{rs}(443)$

SeaWiFS $R_{rs}(443)$

22 April 2003
Another European merged product (GlobColour) for the same day, for comparison

OC-CCI: (Version 3.1)

One of the advantages: Improved spatial coverage (User Requirement)

On sinusoidal grid, OC-CCI coverage is ~30% higher for this example

Note: CMEMS is using OC-CCI products as standard products

Example:
Daily Chlorophyll Concentration (mg m\(^{-3}\)) OC-CCI
22 April, 2003
In situ database

Chlorophyll database
Version 2:
39,849 observations

Note: Improved coverage in the Arctic

Chlorophyll database
Version 3:
66,226 observations

Chlorophyll database
Version 3.1:
79,924 observations

Note: Improved coverage in the Southern Ocean
Match-up Data Analysis

OCCCI v2 Chla matchup performance

\[ r^2 = 0.79 \]
\[ V = 0.33 \]
\[ A = 0.33 \]
\[ \delta = -0.028 \]
\[ S = 0.86 \]
\[ I = 0.0083 \]
\[ n = 7958 \]

OCCCI v3 Chla matchup performance

\[ r^2 = 0.76 \]
\[ V = 0.31 \]
\[ A = 0.31 \]
\[ \delta = 0.0066 \]
\[ S = 0.72 \]
\[ I = -0.056 \]
\[ n = 14582 \]
From Optical Classes to Uncertainty Estimates

Dominant Optical Water Class, July 04-08 2004

- The OC-CCI product suite includes data on optical water classes.
- Match-up in situ data are sorted according to optical classes to establish uncertainties (bias, RMSD) per optical class.
- At each pixel, uncertainties are weighted according to membership of optical classes at that pixel, to generate uncertainty characteristics per pixel.
- Thus, validation using match-ups underpin uncertainty estimates.

Moore et al. 2009
Jackson et al. 2017
Assessment of the Rrs Uncertainties
Version 3: Blended algorithm
- less noisy in oligotrophic waters, better performance in turbid coastal waters

Jackson et al. 2017
Ocean Colour CCI Products

Product suite includes Chl-a, $K_d$ at 490 nm, $R_{rs}$ and inherent optical properties at SeaWiFS wavelengths, their uncertainty estimates and optical water classes.

Oceancolour.org
OC-CCI data processing

- MERIS
- SeaWiFS
- MODIS
- VIIRS 2012-present
- Sentinel 3 2016-present

Atmospheric Correction using best algorithms for each sensor from round-robin comparison

Band shifting, Merging, Bias Correction

Ocean products using best algorithms from round-robin comparisons

Quality Control and Scientific Analysis

Unified multi-sensor Products

Uncertainty characterisation

Global In-situ database

User Community

- Modellers
- Oceanographic Scientists
- Earth Observation Scientists

http://www.oceancolour.org/
Sensors currently contributing to OC-CCI merged product

<table>
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<tr>
<th></th>
<th>412</th>
<th>443</th>
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<tr>
<td>VIIRS</td>
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<td>486</td>
<td>551</td>
<td>671</td>
<td>745</td>
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Consistency in ocean-colour band set in the Sentinel Era

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Considerable improvement over status quo for climate applications. Anticipated advantages include:

- Consistency in constellation of satellite sensors, consistency with MERIS
- Continuity: backwards to MERIS and forward with Sentinel-3 series (operational sensors)
- Coverage: at least two sensors in orbit at the same time
- Better spectral resolution – important for atmospheric correction, novel algorithms, new products
- Ground segment that includes high-quality in situ data acquisition for product validation

But: gap in time between MERIS and OLCI is a challenge

OC4 Chl-a from OLCI: Polymer

1-7 April, 2017
Comparison of daily composites

Daily Rw443 composites (22 September, 2016)

Standard product

Polymer

• Compared with VIIRS-only time series, the improved coverage from OLCI is remarkable.
• But quality assurance for climate products has to be undertaken meticulously, before merging with existing time series.
• Need to exploit the additional spectral coverage provided by OLCI.

Dall’Olmo et al. (2012)
Brewin et al. (2016)
Comparison between trends in Chla obtained over 10 years between OC-CCI and single-mission products:

OC-CCI: SeaWiFS+MERIS+MODIS-A+VIIRS

[10/1997-09/2015] (18 years)

Only significant ($p<0.05$) trends are shown.

Mélin et al., Remote Sens. Environ., 2017
Regionally-differentiated Impact of El Niño on Phytoplankton

Racault et al. 2017
July Chlorophyll fields in the Arabian Sea

MODIS July Climatology from NASA

SeaWiFS July Climatology from NASA

CZCS July Climatology from NASA

OC-CCI July 2003
The Gulf of Guinea is a dynamic and complex ecosystem along the equatorial West African coasts. The use of ocean color data is extremely valuable to study this ecosystem but has been hampered so far by the poor coverage of satellite data (particularly in winter and the Niger delta).

OC-CCI products allow a monthly coverage and reveal the relationships between Chla and physical variables.

Coverage (%) of satellite products as a function of time (A) and spatial cell (B)

Nieto and Mélin, *Prog. Oceanogr.*, 151, 97-115, 2017
Contribution to Ocean Heat Budget

Spectral Optical Model

PAR, CHL, MLD
From ECV to Carbon Observations from Space

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Products</th>
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</thead>
<tbody>
<tr>
<td>Ocean Colour</td>
<td>Chlorophyll, Absorption by coloured dissolved organic matter, Daily photosynthetically-available radiation, Particulate organic carbon, Phytoplankton carbon, Primary production, Particle size distribution, Primary production, New (export production, Phytoplankton functional types</td>
</tr>
<tr>
<td>Infra-red radiometer, passive microwave</td>
<td>Sea-surface temperature</td>
</tr>
<tr>
<td>Active and passive microwave sensors</td>
<td>Wind speed, vector wind, sea state, Sea ice extent, ice edge structure</td>
</tr>
<tr>
<td>Altimeter</td>
<td>Surface geographic currents and eddies</td>
</tr>
</tbody>
</table>

- Satellite requirements consistent with GCOS requirements
- But report emphasises the need for carbon products
- Requirements include both variables and fluxes
Modelling Primary Production

New analytic solutions to production profile
Kovač et al. 2016

Models exist. New analytic solutions have been found for non-spectral case.
Data from Hawaii Ocean Time Series.
Key to model performance is the assignment of model parameters.
At HOT stations, province-based parameter assignment led to underestimation of production.

Kovač et al. 2015
Photosynthesis Irradiance Parameters from Space

In situ database:
Bouman, Platt, Doblin, Gudmundsson, Hickman, Hiscock, Jackson, Lutz, Mélin, Rey, Pepin, Segura, Tilstone, Uitz, van Dongen-Vogels, Sathyendranath

Assimilation Number (mg C Chl\(^{-1}\) h\(^{-1}\))

Global satellite products of photosynthesis-irradiance parameters
Phytoplankton Carbon and Carbon-to-Chlorophyll Ratio: Comparison of some empirical and physiological models

Jackson et al. (2017) CLEO Special Issue (under review)
Comparison of Algorithms for Phytoplankton Carbon (PC) from Ocean Colour
Comparison of algorithms for Particulate Organic Carbon (POC) from Ocean Colour

Evers-King et al. 2017 CLEO Special Issue (under review)
Above-water PAR comparable to NASA MERIS PAR.

Scalar PAR below surface, 0.1° spatial resolution derived from MERIS.

Spectral and directional PAR can be derived from look-up-tables of clear and total overcast skies, latitude, date and wind speed.

Being evaluated currently by some users

Precursor for an OLCI product

Frouin et al. 2017, Platt et al. 2017, CLEO Special Issue
The future of OC-CCI

OC-CCI was conceived as a system in dynamic evolution.

Future lies with CCCS and CCI+

- Important to keep products up-to-date and current
- Coastal products have to be improved
- Sentinel series have to be incorporated
- Synergy with other ECVs has to be exploited
- Extension to inland water bodies important
- Extension of product line (primary production, carbon, PFTs) is crucial for user engagement
- In situ validation programmes have to keep pace with expanding products (e.g. photosynthesis parameters)

What sets OC-CCI apart from the perspective of the climate user?

- Improved coverage (studies of phenology)
- Uncertainty estimates on a per-pixel basis (data assimilation)
- Inter-sensor bias correction (trend analysis)
- Band-shifting (algorithm implementation)
- Rigorous, quantitative algorithm selection (all applications)
Acknowledgements

• This has very much been a community effort, and we thank all who contributed to the work, and all users who provided feedback.

• The NASA team has been very helpful all along the way.

• A special thank you to Peter Regner, ESA, who has been technical officer for OC-CCI all these years.