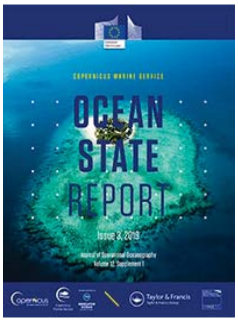

Journal of Operational Oceanography

ISSN: 1755-876X (Print) 1755-8778 (Online) Journal homepage: https://www.tandfonline.com/loi/tjoo20

Copernicus Marine Service Ocean State Report, Issue 3

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To cite this article: Karina von Schuckmann ((Editor)), Pierre-Yves Le Traon ((Editor)), Neville Smith (Chair) ((Review Editor)), Ananda Pascual ((Review Editor)), Samuel Djavidnia ((Review Editor)), Jean-Pierre Gattuso ((Review Editor)), Marilaure Grégoire ((Review Editor)), Glenn Nolan ((Review Editor)), Signe Aaboe, Eva Aguiar, Enrique Álvarez Fanjul, Aida Alvera-Azcárate, Lotfi Aouf, Rosa Barciela, Arno Behrens, Maria Belmonte Rivas, Sana Ben Ismail, Abderrahim Bentamy, Mireno Borgini, Vittorio E. Brando, Nathaniel Bensoussan, Anouk Blauw, Philippe Bryère, Bruno Buongiorno Nardelli, Ainhoa Caballero, Veli Çağlar Yumruktepe, Emma Cebrian, Jacopo Chiggiato, Emanuela Clementi, Lorenzo Corgnati, Marta de Alfonso, Álvaro de Pascual Collar,

Table 3.3.1. Comparison of the data quality during the first quarter of 2017 for all satellite data (All), outside the first 15 km off the coast (Non_coast), subsampling by onshore and offshore flights, for Sentinel-3A (S3) and Jason-3 (J3); for bias [in m], root mean square error [in m] (RMSE), Scatter Index (SI), Correlation coefficient (CORR).

	All		Off coast		Oncoast		Onshore		Offshore	
	J3	S3	J3	S3	J3	S3	J3	S3	J3	S3
RMSE	0.280	0.278	0.280	0.277	0.279	0.301	0.271	0.299	0.283	0.303
BIAS	0.017	−0.032	0.017	0.030	0.028	−0.060	0.052	−0.077	0.016	0.044
SI	0.245	0.239	0.245	0.237	0.264	0.293	0.279	0.282	0.258	0.304
CORR	0.879	0.888	0.880	0.891	0.858	0.784	0.843	0.778	0.864	0.792
Slope	1.012	0.970	1.012	0.972	1.023	0.924	1.062	0.902	1.009	0.945
RV	0.706	0.748	0.708	0.754	0.634	0.518	0.464	0.530	0.673	0.504

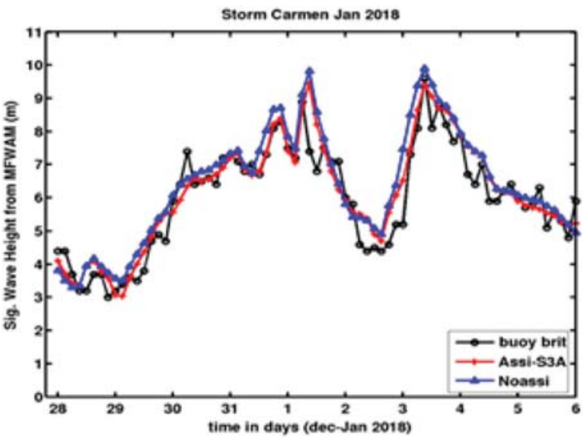

Figure 3.3.4. Time series of significant wave heights at Brittany buoy location during the storm Carmen in early January 2018. Black, red and blue lines indicate significant wave heights from the buoys, the model MFWAM with and without assimilation, respectively.

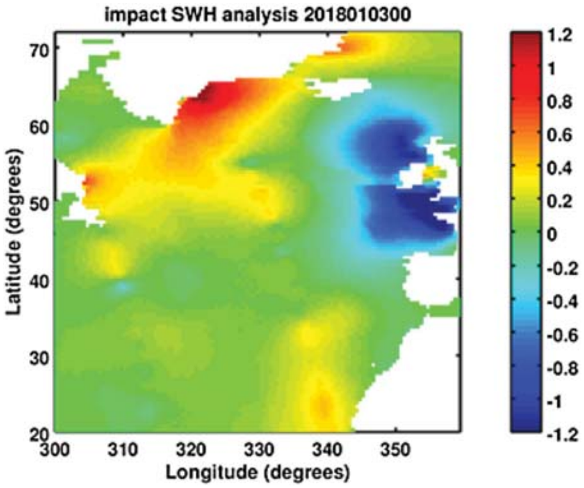

Figure 3.3.5. Difference of significant wave height (in metres) from the wave model MFWAM (Météo-France WAve Model) with and without assimilation on 3 January 2018 at 0:00 UTC. Positive and negative analysis increment stand for an overestimation and underestimation of SWH of the model, respectively. Data source is from 3.3.1.

The assimilation of S3A wave data corrects the misfit of the wave model mostly because of uncertainties related to the wind forcing provided by the atmospheric system. Figure 3.3.5 illustrates the time series of significant wave heights during Carmen at Brittany buoy which is located at 47.5°N and 8.7°W. The validation of the assimilation during the Carmen storm with Brittany buoy has showed an improvement of the normalised scatter index of significant wave height from 12.2% to 10.1%. The assimilation of five altimeters including S3A enhances the impact during storm Carmen and reduces the normalised scatter index of significant wave height to 9.7%. This indicates that such performance of global CMEMS-MFC will ensure better wave products for user applications in many ocean basins.

3.4. Joint Monitoring Programme of the EUtrophication of the NOrthSea with SATellite data user case

Authors: Dimitry Van der Zande, Marieke Eleveld, Heloise Lavigne, Francis Gohin, Silvia Pardo, Gavin Tilstone, Anouk Blauw, Stiig Markager, Lisette Enserink

Statement of main outcome: During the second cycle of the MSFD assessment, incomparability of monitoring methods for chlorophyll-a (CHL) was identified as a main issue hampering a coherent assessment of the eutrophication state of the North Sea. Operational satellite-based ocean colour products provide a solution as they are neutral, transparent and provide cross-boundary information on the CHL state of the North Sea. However, to this day, satellite-based CHL is generally not used in official MSFD reporting. We present the technical steps needed to generate a harmonised CHL indicator map from publicly available CHL products and bridge the gap between the ocean colour community and national monitoring teams/policy makers. This harmonised CHL indicator product enables the progression from point-by-point and country-by-country analyses, to basin-wide analysis of the eutrophication state. Finally, we evaluate the quality of the satellite-based CHL products by a comparison analysis with *in situ* datasets for different assessment areas in the Greater North Sea.

Products used:

Ref. No.	Product name and type	Documentation
3.4.1	OCEANCOLOUR_ATL_CHL_L3_REP_OBSERVATIONS_009_067	PUM: http://marine.copernicus.eu/documents/PUM/CMEMS-OC-PUM-009-ALL.pdf QUID: http://marine.copernicus.eu/documents/QUID/CMEMS-OC-QUID-009-066-067-068-069-088-091.pdf
3.4.2	OCEANCOLOUR_ATL_CHL_L3_REP_OBSERVATIONS_009_098	PUM: http://marine.copernicus.eu/documents/PUM/CMEMS-OC-PUM-009-ALL.pdf QUID: http://marine.copernicus.eu/documents/QUID/CMEMS-OC-QUID-009-033-037-082-098.pdf
3.4.3	OCEANCOLOUR_ATL_OPTICS_L3_REP_OBSERVATIONS_009_066	PUM: http://marine.copernicus.eu/documents/PUM/CMEMS-OC-PUM-009-ALL.pdf QUID: http://marine.copernicus.eu/documents/QUID/CMEMS-OC-QUID-009-066-067-068-069-088-091.pdf
3.4.4	OCEANCOLOUR_ATL_OPTICS_L3_NRT_OBSERVATIONS_009_034	PUM: http://marine.copernicus.eu/documents/PUM/CMEMS-OC-PUM-009-ALL.pdf QUID: http://marine.copernicus.eu/documents/QUID/CMEMS-OC-QUID-009-034-036-046-047-087-089-090-092.pdf
3.4.5	OCEANCOLOUR_BAL_CHL_L3_REP_OBSERVATIONS_009_080	PUM: http://marine.copernicus.eu/documents/PUM/CMEMS-OC-PUM-009-ALL.pdf QUID: http://marine.copernicus.eu/documents/QUID/CMEMS-OC-QUID-009-080-097.pdf
3.4.6	OCEANCOLOUR_BAL_CHL_L3_NRT_OBSERVATIONS_009_049	PUM: http://marine.copernicus.eu/documents/PUM/CMEMS-OC-PUM-009-ALL.pdf QUID: http://marine.copernicus.eu/documents/QUID/CMEMS-OC-QUID-009-048-049.pdf
3.4.7	OCEANCOLOUR_BAL_OPTICS_L3_NRT_OBSERVATIONS_009_048	PUM: http://marine.copernicus.eu/documents/PUM/CMEMS-OC-PUM-009-ALL.pdf QUID: http://marine.copernicus.eu/documents/QUID/CMEMS-OC-QUID-009-048-049.pdf
3.4.8	OCEANCOLOUR_BAL_OPTICS_L3_REP_OBSERVATIONS_009_097	PUM: http://marine.copernicus.eu/documents/PUM/CMEMS-OC-PUM-009-ALL.pdf QUID: http://marine.copernicus.eu/documents/QUID/CMEMS-OC-QUID-009-080-097.pdf

The Marine Strategy Framework Directive (MSFD) is currently one of the most important drivers for monitoring the coastal and offshore waters in Europe with the objective of reaching a 'good environmental status' (GES) by 2020 (Gohin et al. 2008). It is a crucial legal instrument of the European Commission to protect the marine environment including its ecosystems and biodiversity. Human-induced eutrophication is one of the criteria for assessing the extent to which GES is being achieved. Eutrophication can be defined as the enrichment of water by nutrients causing an accelerated growth of algae and higher forms of plant life to produce an undesirable disturbance to the balance of organisms present in the water and to the quality of the water concerned, and therefore refers to the undesirable effects resulting from anthropogenic enrichment by nutrients (OSPAR 2017).

The eutrophication status is established by monitoring of nutrients, and CHL concentration as a proxy of phytoplankton biomass. More specifically, the indicator of choice is the 90-percentile of the CHL concentrations (CHL-P90) over the phytoplankton growing season (i.e. March–September incl.) for a period of six years expressed in $\mu g\, l^{-1}$ or $mg\, m^{-3}$. CHL-P90 represents the CHL level such that 90% of the observations are equal to or less than this value. While *in situ* data acquisition is still considered as the main monitoring tool, the European Commission highlighted the need for greater coherence with related EU legislations (Water Framework Directive and Habitats and Birds Directive) and for more coherent and coordinated approaches within and between marine regions and sub-regions (European Commission 2014). While preparing for the second cycle of MSFD assessment, various OSPAR groups (Intersessional Correspondence Group on Eutrophication (ICG-EUT) and the Hazardous Substances and Eutrophication Committee (HASEC)) have identified incomparability of monitoring methods for CHL as a main issue hampering a coherent assessment of the common indicator CHL in the Greater North Sea. Moreover, the assessment levels for CHL, based on background concentrations, have been determined with different methods between member states. This results in different GES determinations across national borders that cannot be explained by differences in water quality (Figure 3.4.1). Additionally, the budgets for marine monitoring are decreasing in many European countries forcing them to efficiently use monitoring resources.

During recent years, there has been a growing tendency to use optical remote sensing as a supporting tool to achieve the monitoring requirements because of severe resource constraints of available ship time and personnel and the need for a coherent assessment of CHL between all OSPAR member states bordering the North Sea. Satellite data of CHL combine cheaper data

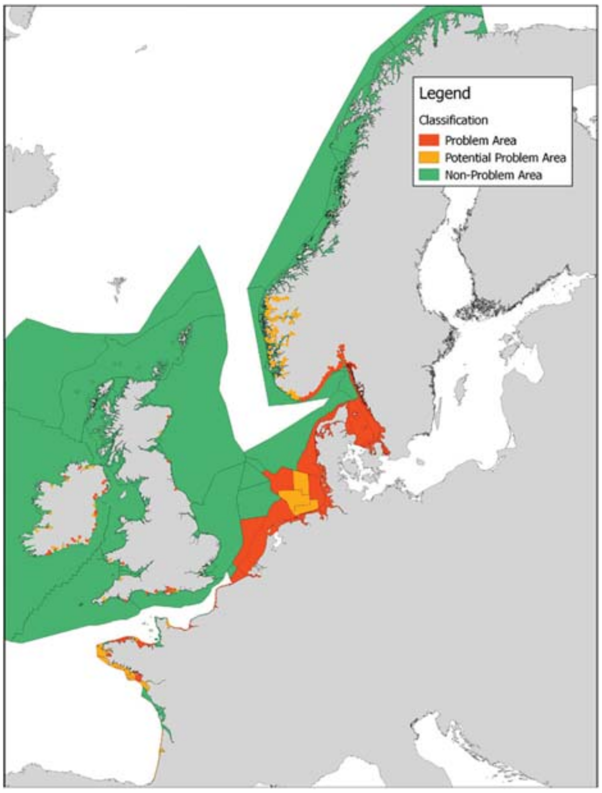

Figure 3.4.1. Map of problem areas for eutrophication for the North Sea region produced by the OSPAR Common Procedure by evaluating the primary indicators (nutrient concentrations, chlorophyll-a and dissolved oxygen) and one secondary criteria (Phaeocystis). For the problem areas measures need to be taken to reduce or eliminate the anthropogenic causes of eutrophication (OSPAR 2017).

collection with a much improved geographical and temporal coverage compared to traditional *in situ* data.

The two-year EU-project Joint Monitoring Programme of the EUtrophication of the NOrth-Sea with SATellite data (JMP-EUNOSAT, Feb. 2017-Feb. 2019) aims at developing a coherent set of assessment levels and a cost-effective GES assessment for eutrophication in the Greater North Sea. The consortium consists of 14 partners[1] from all countries bordering the North Sea.

Satellite data from ocean colour sensors (i.e. SeaWiFS, MODIS, MERIS, VIIRS, Sentinel-3) can provide spatially coherent data on CHL concentrations using CHL retrieval algorithms. There has been considerable success with blue/green-ratio algorithms such as OC4 (O'Reilly et al. 1998) and OC5 (Gohin et al. 2002) in case 1 waters where the variation of optical properties (absorption and scattering) is dominated by phytoplankton and associated material. In contrast, the optical complexity in coastal waters often poses many challenges to the accurate retrieval of biogeochemical parameters using satellite remote sensing (Sathyendranath 2000; Lee 2006). CHL retrieval by blue/green-ratio algorithms tend to fail when applied to coastal waters whose optical properties are strongly influenced by non-covarying concentrations of suspended particulate matter (SPM) and coloured dissolved organic matter (CDOM). Such waters are defined as case 2 waters. Several constituent retrieval algorithms for use in case 2 waters have been developed: (1) red-edge algorithms (Gons et al. 2005) taking advantage of the CHL absorption peak near 670 nm and (2) artificial network approaches trained to varying parameter concentrations and optical property ranges specifically developed for use with MERIS data, such as the MERIS Ground Segment Processor (MEGS; Doerffer and Schiller 2007) and the FUB/WeW (Schroeder et al. 2007).

The technical objective of JMP EUNOSAT is to evaluate publicly accessible satellite-based CHL products available from CMEMS, ODESA and IFREMER, and determine their validity for different water types, e.g. clear, turbid or CDOM-rich waters, so that the choice of satellite product is determined by environmental conditions per (cross-border) assessment area, rather than national boundaries of the member states.

We started from a collection of well-validated operational satellite-based CHL products for the Greater North Sea: (1) CMEMS OC5-CI (product 3.4.1), (2) CMEMS GSM (product 3.4.2), (3) CMEMS OC4 adapted to Baltic waters (product 3.4.5 and 3.4.6), (4) OC4 applied to CMEMS remote sensing reflectance products (product 3.4.3 and 3.4.4) and (5) MEGS 7.5 applied to the MERIS archive obtained from ODESA online (http://www.odesa-info.eu/). For each of these products it was determined for which water types, described in terms of remote sensing reflectance (RRS) spectra (product 3.4.3, 3.4.4, 3.4.7 and 3.4.8), they provided the most accurate CHL estimations (i.e. relative error < 50%) based on a variety of reference datasets from the CoastColour Round Robin (CCRR) project[2] (Nechad et al. 2015). These reference data sets were specifically designed to test algorithms and assess their accuracy for retrieving water quality parameters and comprise 5000 matchups of CHL concentrations and hyperspectral RRS-spectra covering a wide range of water types in terms of CHL, SPM and CDOM concentrations. The RRS-spectra were used as input to the considered CHL algorithms and their resulting CHL estimates were compared to the reference values allowing the development of a pixel-based quality assessment.

Figure 3.4.2(A,B) shows the application of this approach on satellite observations for the 8th of April 2010 for the OC4 and OC5 products showing an algal bloom in the Belgian and Dutch coastal waters. Figure 3.4.2(C,D) shows a classification map indicating the water types where the OC4 and OC5 algorithms

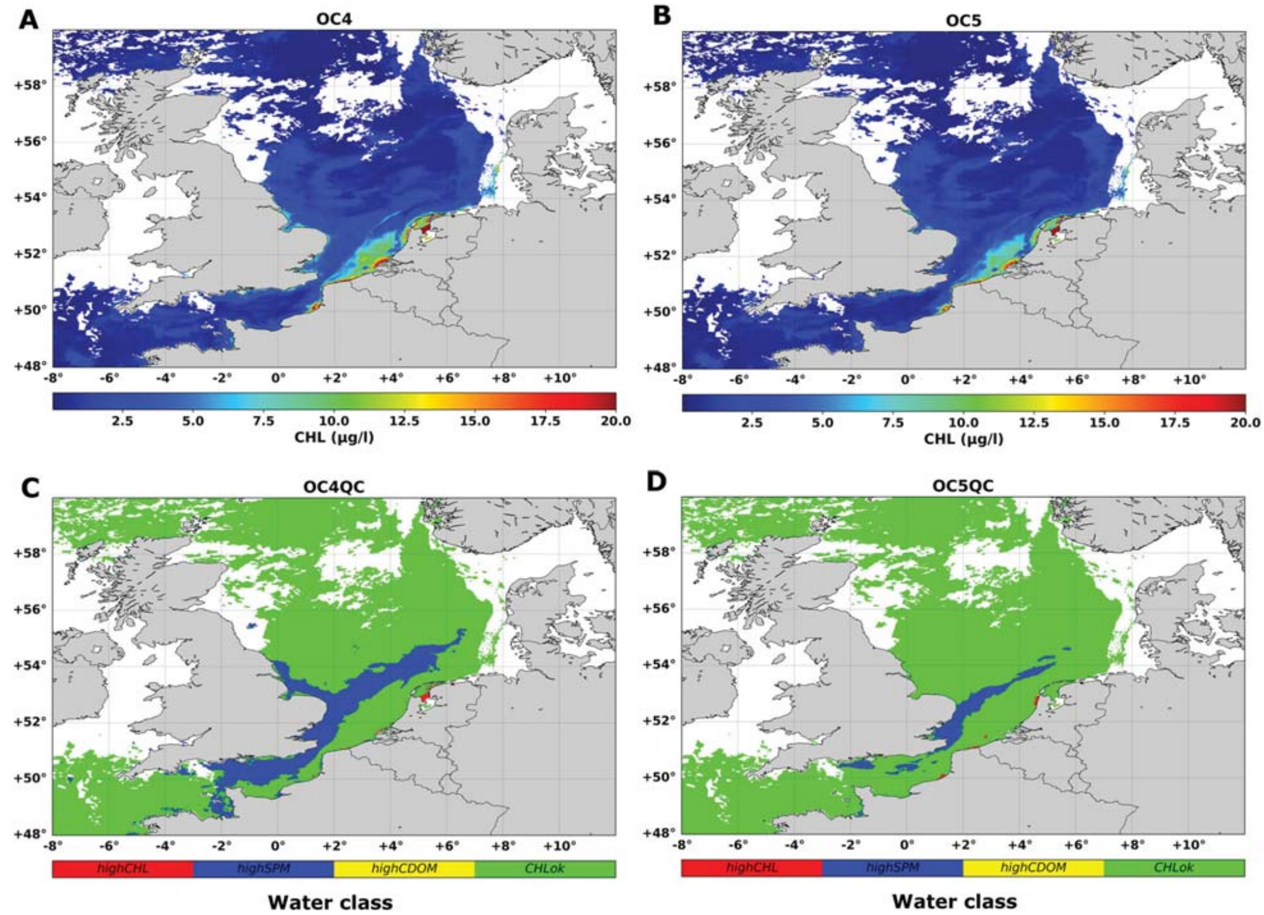

Figure 3.4.2. (A and B) CHL products generated using the OC4 and OC5 algorithms for the 8th of April 2010 showing an algal bloom in the Belgian and Dutch coastal waters. (C and D) Water type classification map indicating the water types where the OC4 (C) and OC5 (D) algorithms are applicable indicating that OC5 can be applied in more situations than OC4. These products are merged on a pixel by pixel basis with a priority rule given to OC4, then OC5 and finally MEGS 7.5 filling up the map with the most appropriate algorithms available for different water types (based on validation analysis, data not shown): clear waters with OC4, moderately turbid waters with OC5 and highly turbid waters with MEGS 7.5. OC4 is inaccurate in the English Channel and South-East UK due to high concentrations of suspended matter (SPM). Cloud cover is presented in white, i.e. no is data available. In case no clouds are present, but both OC4 and OC5 are not applicable, the MERIS MEGS 7.5 product is used. If that product is also not suitable we have no reliable data for that specific day. The main goal of this approach is to eliminate erroneous data from the process.

are applicable indicating that the OC5 algorithm can be applied in more situations than the OC4 algorithm. The OC4 algorithm is inaccurate in the English Channel and southeast UK due to high SPM concentrations.

In the next phase of the JMP-EUNOSAT project, a blending process was developed to join CHL datasets based on best suited algorithm/water type combination, with special attention to the transition zones between different water types to ensure a gradual merge. This step enabled the progress from point-by-point and country-by-country analyses, to basin-wide analysis with data that covers gradients in the ecosystem system. This enabled a definition of cross-border assessment areas based on ecosystem characteristics. The blended JMP-EUNOSAT CHL product was compared to available *in situ* datasets for all assessment areas (data not shown). This regional intercomparison will quantify the suitability of used standard products and blending approach for eutrophication assessment. Figure 3.4.3 shows different quality-controlled CHL products (i.e. OC4, OC5, MEGS_7.5) for the 8th of April 2010. These products are merged on a pixel by pixel basis with a priority rule given to OC4, then OC5 and finally MEGS 7.5 filling up the map with the most appropriate algorithms available: clear waters with OC4, moderately turbid waters with OC5 and highly turbid waters with MEGS 7.5.

Intercomparison of satellite products with ship-based observations

The quality-controlled and merged satellite-based CHL observations are compared to *in situ* observations that have been collected in national monitoring programs.

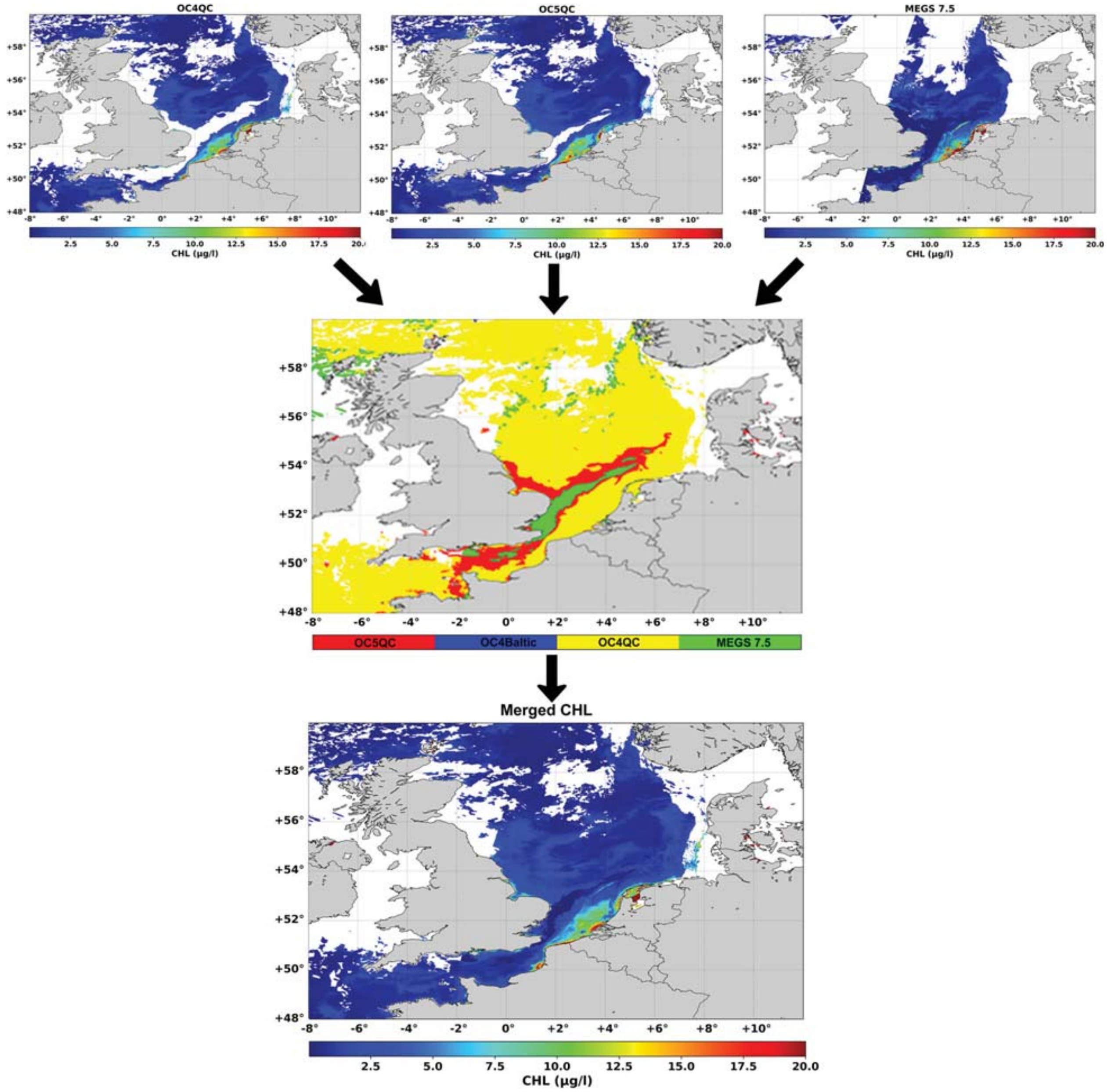

Figure 3.4.3. Blending process of different quality-controlled CHL products on a pixel per pixel basis. The different quality-controlled CHL products (i.e. OC4, OC5 and MEGS_7.5) for the 8th of April 2010 are presented in the top row.

Figure 3.4.4 shows 90-percentile map of CHL for the growing season (March-Sept incl.) of 2003 providing a spatial interpretation of the intensity of the algal blooms in the North Sea. Additionally, CHL time series are provided for the national monitoring stations Stonehaven (Scotland), Rottumerplaat 50 (The Netherlands), 330 (Belgium) and Boulogne (France) for the year 2003 showing the ability of the satellite data to capture the temporal CHL dynamics. The *in situ* measured CHL was analysed using the HPLC-method. For the time series of satellite data, we extracted a 3 × 3 macropixel and the 1 × 1 km centre pixel containing the monitoring station location. The resulting time series are presented in monthly bins as *in situ* data is mostly collected on a monthly basis in these stations. The satellite data is presented as boxplots to demonstrate the increased availability of satellite data compared to *in situ* sampling, i.e. 20–50 observations per growing season depending on the location, cloud cover and water conditions.

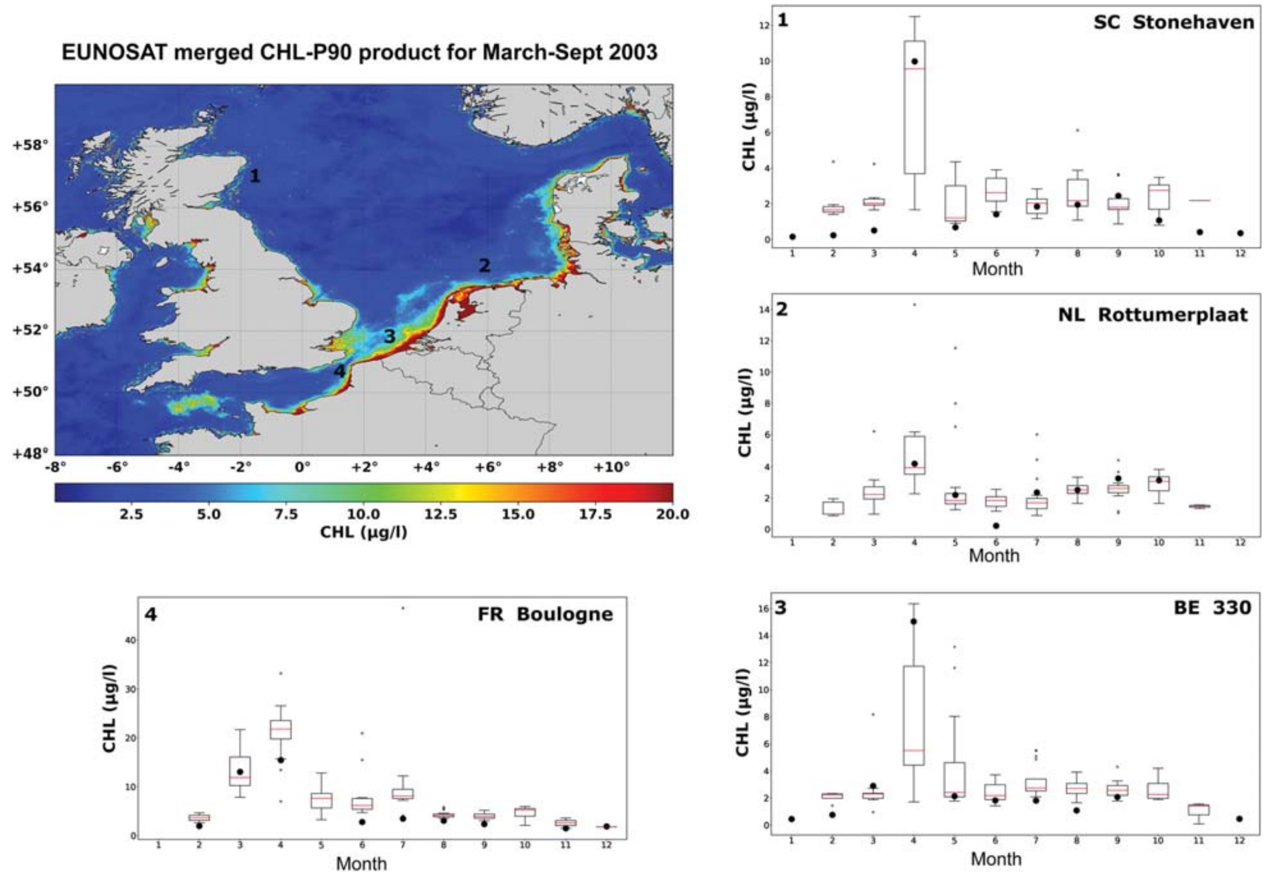

Figure 3.4.4. Map of the 90th percentile of the blended and quality-controlled CHL product for the growing season (March–September incl.) of 2003 providing a spatial interpretation of the intensity of the algal blooms in the North Sea. Additionally, a direct comparison of CHL time series, presented as boxplots, is provided for the national monitoring stations Stonehaven (Scotland), Rottumerplaat (The Netherlands), 330 (Belgium) and Boulogne (France) for the year 2003 showing the ability of the satellite data to capture the temporal CHL dynamics. Black dots represent the mean monthly in-situ CHL concentration, the boxplots show the monthly satellite-based CHL concentration with box extending from the lower to upper quartile values of the data, with a line at the median and the whiskers showing the 10- and 90-percentiles.

Towards operational collaboration between North Sea Countries

For efficient monitoring of eutrophication, it is advised to combine all available monitoring platforms, i.e. dedicated monitoring surveys taking water samples, Ferryboxes mounted on ‘ships of opportunity’ and satellite observations. In this way, the strengths and weaknesses of one platform can be compensated by another in terms of spatial and temporal resolution, sampling depth, ability to measure different variables, analytical precision and costs. To enable such a combined use of different data sources, there is a need for a scientifically sound procedure to feed data collected with different methods into one common indicator for the assessment (e.g. CHL) describing both the state and the development of the pelagic environment. Data distribution centres such as CMEMS play a key role in this endeavour as they provide validated ocean colour products as input for the JMP-EUNOSAT processing chain. With the Copernicus program guaranteeing a reliable source of data to at least 2036, special efforts are made to ensure future integration of Sentinel-3/OLCI data into the processing chain. Sentinel-3/OLCI has a similar spectral bandset as MERIS which is useful to provide more reliable results in turbid coastal waters. Additionally, the full resolution data (300 m spatial resolution) will provide more robust CHL estimates close to the coast.

3.5. Regional mean time series for the Northwest European Shelf Seas

Authors: Jonathan Tinker, Richard Renshaw, Rosa Barciela, Richard Wood

Statement of main outcome: We have developed a set of regional mean time series to aid Copernicus Marine Environmental Monitoring Service (CMEMS)