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PROJECT

Optical remote sensing of marine and inland waters ("BELCOLOUR-2")

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List of Abbreviations

AHS	Airborne Hyperspectral Scanner (an airborne sensor)
APEX	Airborne Prism Experiment (an airborne sensor)
AQUA	A NASA-operated satellite
AVHRR	Advanced Very High resolution Radiometer (a spaceborne sensor)
CDOM	Coloured Dissolved Organic Matter
Chl	Chlorophyll a, a phytoplankton pigment
CO_2	Carbon Dioxide
DINEOF	Data Interpolating Empirical Orthogonal Function, a data processing technique
ENVISAT	A ESA-operated satellite
EO	Earth Observation
ESA	European Space Agency
GOCI	Geostationary Ocean Color Imager (a spaceborne sensor)
IOP	Inherent Optical Properties
Kd	Diffuse Attenuation Coefficient
KOSC	Korea Ocean Satellite Center
MERIS	Medium Resolution Imaging Spectrometer (a spaceborne sensor)
METEOSAT	Meteorological Satellites (a series of satellites operated by EUMETSAT)
MODIS	Moderate resolution Imaging Spectrometer (a spaceborne sensor)
NASA	National Aeronautics and Space Administration
NIR	Near Infrared (0.7-1.0μm)
OLCI	Ocean Land Colour Instrument (a spaceborne sensor)
PAR	Photosynthetically Available Radiation
pCO_2	Partial pressure of Carbon Dioxide dissolved in seawater
PSD	Particle Size Distribution
SeaWiFS	Sea-viewing Wide field of view Sensor (a spaceborne sensor)
SEVIRI	Spinning Enhanced Visible and Infrared Imager (a spaceborne sensor)
SIOP	(mass-) Specific Inherent Optical Properties
SPM	Suspended Particulate Matter (another term for TSM)
SST	Sea Surface Temperature
SWIR	Short Wave Infrared (1-3μm)
TSM	Total Suspended Matter (another term for SPM)
UV	Ultraviolet

Executive Summary

This report describes the research carried out in the framework of the BELCOLOUR-2 project, funded as a thematic network by the Belgian Science Policy Office (BELSPO) STEREO programme over the period December 2006-December 2011.

The general objective of the BELCOLOUR-2 project was "to improve the quality of existing optical remote sensing products for marine and inland waters based on new knowledge and to develop new products (including primary production and partial pressure of CO_2) for key applications such as aquaculture and air-sea CO_2 fluxes." BELCOLOUR-2 benefited from the experience built up in the previous BELCOLOUR-1 project (2002-6) whose results can be found at http:www.mumm.ac.be/BELCOLOUR.

During the duration of the BELCOLOUR-2 project (Dec 2006-Dec 2011) there has been enormous progress in the field of ocean colour remote sensing. This progress has been driven by the availability of high quality, easily available satellite data, particularly from the MODIS-AQUA and MERIS sensors. Progress in algorithms for retrieval of new parameters has been considerable and the basic products of chlorophyll a and Total Suspended Matter concentration are now joined by a host of new products and applications, including phytoplankton species, coloured dissolved organic matter, turbidity, algae bloom timing, CO_2 partial pressure, etc. Improvements in *in situ* instrumentation have allowed the study of microscale particulate optics. There have been improvements in many aspects of our understanding of absorption and scattering processes in the sea and how these processes are related to geophysical or ecosystem parameters and processes. These more fundamental studies build the basis for longer term potential applications of ocean colour remote sensing, revealing more and more information on marine processes. The BELCOLOUR-2 project has contributed to these developments by publishing research on a number of key issues and by presenting these at numerous workshops and conferences. These contributions are described briefly in this report and in detail in the corresponding publications, covering the following topics:

- Spectral variation of particulate scattering, including the impact of absorption and the differentiation between non-algae particles and blooms of *Phaeocystis globosa*
- Mass-specific side, back and total scattering of particles, and characterisation of variability
- Spectral variation of Coloured Dissolved Organic Matter (CDOM) absorption and the relation between spectral slope and CDOM origin
- A detection algorithm for *Phaeocystis globosa*
- A detection algorithm for *Noctiluca scintillans*
- Detection of high biomass algal blooms
- Estimation of Total Suspended Matter for airborne and polar and geostationary satellite remote sensing
- Estimation of turbidity in moderately and extremely turbid waters
- Variation of marine reflectance in the Short Wave Infrared
- Use of geostatistical techniques for cloud filling and outlier detection
- Atmospheric correction of geostationary remote sensing data
- Detection and correction of adjacency effects
- Atmospheric correction for extremely turbid waters
- Estimation of the diffuse attenuation coefficient
- Estimation of CO_2 partial pressure

- Estimation of primary production

Most of these studies contain a validation element.

The exploitation of remote sensing data is also described in a number of applications including ecosystem modelling, sediment transport, primary production, algae bloom dynamics and the genetic adaptation of marine visual predators.

Finally a number of challenges and opportunities are outlined for possible future research.

1.Introduction

1.1.Scope and project objectives

This report describes the research carried out in the framework of the BELCOLOUR-2 project, funded as a thematic network by the Belgian Science Policy Office (BELSPO) STEREO programme over the period December 2006-December 2011.

The general objective of the BELCOLOUR-2 project was "to improve the quality of existing optical remote sensing products for marine and inland waters based on new knowledge and to develop new products (including primary production and partial pressure of CO2) for key applications such as aquaculture and air-sea CO2 fluxes." BELCOLOUR-2 benefited from the experience built up in the previous BELCOLOUR-1 project (2002-6) whose results can be found at http:www.mumm.ac.be/BELCOLOUR.

BELCOLOUR-2 aimed to improve the theoretical basis for solving key problems in optical remote sensing with the specific research objectives to:

- o Improve the quality and the quality control of existing EO products for total suspended matter, chlorophyll a and diffuse attenuation.
- o Develop and validate algorithms for detection and correction of adjacency effects and for detection/correction/mapping of bottom effects
- o Improve and validate algorithms for atmospheric correction, particularly aspects concerning turbid waters, moderate sun glint and absorbing aerosols.
- o Develop new algorithms for phytoplankton-related parameters including phytoplankton taxonomic groups and determine their range of applicability (detection limits, limitations on feasibility related to optical water type).
- o Develop new products, such as PAR attenuation and partial pressure of CO2, for use with ecosystem and carbon cycle models in an integrated assessment of primary production and air-sea CO2 fluxes.
- o Provide the basic research to support the design of new sensors.

In addition to these scientific objectives, BELCOLOUR-2 had the exploitation objectives to:

- o Facilitate use of products for marine, coastal and inland water applications by consulting and supporting key user groups and by tailoring products according to feedback.
- o Contribute to the international science community by disseminating research results, organising workshops and training scientists.

1.2.State of art at beginning of the project

The BELCOLOUR-2 proposal was written in July 2006 and the project started in December 2006. The general objectives of the project have been retained throughout the period 2006-2011 and the research directions identified in 2006 have been globally respected. However, BELCOLOUR2 has been carried out within an international context of optical remote sensing of coastal and inland waters that has been particularly dynamic over the last 5 years.

As just one example of this evolution, in 2006 data from polar-orbiters such as SeaWiFS, MODIS-AQUA and, to a lesser extent, MERIS were beginning to become more easily available. However, issues regarding data availability and distribution (particularly for near real-time applications) and concerns about data quality were severe for coastal and inland waters and operational applications were very limited. The idea of **ocean colour sensors in a geostationary orbit** was a dream for a few scientists putting forward long-term ideas to space agencies, but was thought by most to be technically infeasible or at least decades away or was simply too far from the SeaWiFS/MODIS/MERIS mainstream to be even envisaged. Since then, this situation has changed radically. The study of (Neukermans et al. 2009) has demonstrated the feasibility of remote sensing of tidal variability of Total Suspended Matter from SEVIRI, a meteorological sensor onboard the geostationary METEOSAT Second Generation platform. Furthermore, the launch in 2010 of the Korean GOCI sensor and the successful processing and distribution of data in 2011 has demonstrated that the stringent signal:noise and spatial resolution requirements of a dedicated ocean colour sensor, with the capability of estimating chlorophyll concentration, can be achieved from the geostationary orbit. The data available for marine applications of optical remote sensing then goes from one image per day to many images per day (e.g. up to 8 from GOCI), dramatically improving the possibility of achieving daily coverage of a region during periods of scattered clouds, and allowing the study of previously unresolved high frequency marine processes with tidal variability (sediment advection and resuspension) or diurnal variability (vertical migration, photosynthetic yield of phytoplankton). The advent of geostationary ocean colour may even lead to entirely new ways of data processing, moving from the pixel-by-pixel approach currently adopted for all sensors to methods that exploit temporal coherency as an extra constraint for data processing algorithms.

Although the progress with satellite/sensor hardware and data availability has perhaps been the most remarkable over the period 2006-2011, significant progress, both technological and scientific, has been made in other directions relating to the BELCOLOUR-2 objectives. In situ instrumentation for marine optics measurements has steadily improved, enabling new parameters and processes to be measured. Of particular importance for ocean colour remote sensing is the **particulate backscatter coefficient**, which was not commonly measured in 2006. For example, the key studies of variability of inherent optical properties carried out by (Babin et al. 2003; Babin et al. 2003) measured only particulate scattering and absorption but not backscattering. Use of those datasets in remote sensing applications was then subject to assumptions on the scattering:backscattering ratio, generally assumed constant spatially, spectrally and temporally and equal to the ratio reported by (Petzold 1972) based on measurements in San Diego bay in the early 1970s. Since 2006, measurement of the particulate backscatter coefficient has become more ubiquitous and has been reported for a number of regions by, e.g. (McKee and Cunningham 2006; Snyder et al. 2008; Blondeau-Patissier et al. 2009; Boss et al. 2009; Neukermans et al. 2012) thus providing a sounder theoretical basis for exploitation or refinement of remote sensing algorithms, e.g. (Nechad et al. 2010), with implicit or explicit assumptions regarding the mass-specific particulate backscatter coefficient.

The BELCOLOUR2 project has, with the full encouragement of BELSPO, responded flexibly to this fast-changing situation taking advantage of a number of new opportunities, many of which were not foreseen in the original proposal (the improved capabilities and availability of in situ instrumentation for particulate backscatter and for reflectance in the Short Wave Infrared, the application interest in light adaptation of visible predators,) or were only vaguely foreseen (the advent of geostationary ocean colour remote sensing, the increased internationalisation of application interest, the growing interest in extremely turbid waters, etc.). The following subsections summarise the extent of knowledge at the beginning of the BELCOLOUR-2 project (Dec 2006) in key areas.

1.2.1. Data quality

Data from sensors such as MODIS and MERIS were easily available for research as a multi-year time series up to near real-time (e.g. BELCOLOUR-1 image archive). However, many problems remain regarding the quality and the quality control of optical remote sensing data. Knowledge of their accuracy over the complete range of water types and atmospheric conditions was seriously lacking. BELCOLOUR-2 aimed to improve the quality control of products by theoretical research into retrieval quality and use results to better mask archived products.

1.2.2. Validation

Validation of optical remote sensing products was (and still is) an essential ongoing activity. Existing databases for validation of products from, e.g. MODIS and MERIS, were relatively sparse in space and time. Particular gaps in validation data existed for near shore and inland waters and for near infrared water reflectance. While protocols and instrumentation had improved significantly in the period 2001-2006 the quantification (and reduction) of measurement uncertainties was difficult. BELCOLOUR-2 aimed to continue validation activities started in BELCOLOUR-1 with greater emphasis on near shore and inland waters, on validation of near infrared reflectance and on quantification of uncertainties.

1.2.3. Phytoplankton optical properties and phytoplankton (taxonomic) groups

The spatial and temporal variability of chlorophyll-specific phytoplankton absorption was recognised as a key source of Chl a retrieval error. Such variability had been explained by accessory pigments varying with species composition or physiological status of cells. However, these relationships needed to be better characterised to reduce the retrieval uncertainties. b) Laboratory results had showed differences in absorption spectra between phytoplankton groups (PGs) e.g. diatoms and Phaeocystis colonies. However, exploitation of these differences using satellite data was less reliable in turbid waters. The ms. BELCOLOUR-2 aimed to develop new algorithms for mapping undesirable algal bloom with a determination of their range of applicability (detection limits related to optical water type). Specific inherent optical properties (SIOP) measurements were required to better understand SIOP variability.

1.2.4. Atmospheric correction

Atmospheric correction was (and still is) a key source of inaccuracy for remotely sensed products. Difficulties included: estimation of aerosol reflectance over turbid waters, for nearshore/inland waters with adjacency effects and for absorbing aerosols; estimation of sunglint; treatment of subpixel scale or thin clouds. BELCOLOUR-2 aimed to improve these components of atmospheric correction algorithms and test with data acquired for various coastal/inland waters, particularly by use of more near infrared or short wave infrared wavelengths; use of aerosol climatologies; coupled water-atmosphere inversion methods

1.2.5. Primary production

Satellite algorithms existed for the estimation of primary production in Case 1 waters based on Chl a and empirical estimates of the light utilisation efficiency. Various formulations (including time-, depth- and wavelength-integrated models) had been developed relating Chl a to rates of photosynthesis. However, most of these models are not applicable to case 2 waters. BELCOLOUR-2 aimed to extend the applicability of primary production algorithms to case 2 waters.

1.2.6. Air-sea CO2 flux

Estimates of air-sea CO2 fluxes are a key element in the climate change context. These fluxes depend on air-water CO2 gradient controlled by physical and biogeochemical processes and the gas transfer velocity. These input parameters may be obtained from a combination of atmospheric models, aquatic (physical and biogeochemical) models and EO data (optical, thermal and radar). However, the uncertainties in these input parameters and their subsequent bias on air-sea CO2 fluxes estimates were still largely unquantified, especially in heterogeneous coastal areas. BELCOLOUR-2 aimed to develop maps of air-sea CO2 flux estimates in the Southern North Sea and English Channel with an emphasis on product uncertainties and specific coastal issues.

1.2.7.New technologies

The availability and quality of remote sensing data is strongly driven by technological developments. Examples of emerging technologies included satellite-based hyperspectral sensors (from UV to SWIR), geostationary sensors (data every 15 minutes), unmanned airborne vehicles (the future of airborne remote sensing?), multiple look angles and possibly LIDAR, etc. BELCOLOUR-2 aimed to design algorithms in a hyperspectral context, test existing geostationary data (METEOSAT Second Generation) and contribute to the design of future sensors via appropriate working groups.

2.Progress in Marine Optics Theory

Algorithms for estimation of marine parameters from ocean colour remote sensing rely on the fundamental theory of marine optics, generally structured via:
A reflectance model expressing marine reflectance as a function of Inherent Optical Properties (IOP) obtained by approximation of a full radiative transfer model.
Relationships linking IOP to the desired marine parameters (e.g. Chlorophyll a concentration, Total Suspended Matter concentration, coloured dissolved organic matter, euphotic depth, etc.) often via a linear Specific Inherent Optical Property (SIOP), e.g. the chlorophyll-specific phytoplankton absorption coefficient.
This two-step approach is not obligatory – suitable algorithms can also be developed directly from marine, or even top-of-atmosphere, reflectance to, say, chlorophyll a. However, the two-step structure facilitates a modular approach to the remote sensing problem, via specific study of individual components, e.g. the relationship between phytoplankton absorption spectrum and chlorophyll a and other pigment concentrations. The BELCOLOUR-2 project has studied in detail the following components of marine optics theory:

- The spectral variation of particulate scattering, from visible to near infrared and including the impact of particulate absorption
- The mass-specific particulate back, side and total scattering coefficients and their characterisation, where possible, as function of particle size and type
- Coloured Dissolved Organic Matter, its spectral slope and origin
- Primary production, including its estimation in case 2 waters

The question underlying much of the BELCOLOUR-2 research on marine optics theory can be summarised as:
"Do specific inherent optical properties vary significantly in space and time and, if so, can this variability be characterised in a way that can be exploited by remote sensing algorithms to give *regional* algorithms that outperform a single optimally designed global algorithm?"

A second question, motivating much marine optics theoretical research, can be formulated:
"**Can new parameters be estimated by optical remote sensing on the basis of hitherto unexploited optical processes**?"

While the first question relates to the refinement of algorithms for existing parameters (chlorophyll a, Total Suspended Matter, etc.) the second motivates longer term research towards parameters that may become available in the future from ocean colour remote sensing. Examples of such parameters may include phytoplankton species composition and particle size distribution for which there is considerable interest from the marine biology and sediment transport communities.

2.1. Particulate spectral scattering – impact of absorption

Subject to certain assumptions including a power law "Junge" type Particle Size Distribution (PSD), the spectral variation of particulate attenuation, c_p is expected by Mie theory to follow a power law (Morel 1973),

$$c_p(\lambda) = c_{p0}(\lambda_0)\left(\frac{\lambda}{\lambda_0}\right)^{-n} \qquad (1.1)$$

where λ represents wavelength and n is the spectral exponent of particulate scattering. n then depends on the size distribution and composition (refractive index) of suspended particulate matter (Babin et al. 2003). A modification of the power law formulation (1.1) for c_p was proposed by (Boss et al. 2001) for absorbing particles. When considered in terms of the particulate scattering coefficient, $b_p(\lambda) = c_p(\lambda) - a_p(\lambda)$, which is more relevant to remote sensing, the effect of particulate absorption, a_p needs to be considered – see Figure 1.

Within BELCOLOUR-2, (Doxaran et al. 2009) studied $b_p(\lambda)$ in a range of coastal waters via field measurements and Mie theory calculations. Instrumentation specially designed to measure particulate scattering in the near infrared range (700-900nm) gave the possibility of distinguishing between particle size effects, present for all wavelengths, and particulate absorption effects, not present for the longest wavelengths.

Results show that a simple power-law function closely reproduces the near-infrared b_p spectral variations, with a spectral slope, n_{bp} varying in the range [0.1 – 1.4]. In the visible (e.g., 440 nm), particulate absorption effects systematically lead to b_p values 5-30% lower than values predicted using a power-law function fitted in the near-infrared and extrapolated to 440 nm. The respective influences of the particle size distribution and composition were investigated. Finally, an empirical model was derived from theoretical calculations to reproduce the actual b_p spectral variations from near-infrared to short visible wavelengths, taking into account particulate absorption effects.

One implication of this study is that improved accuracy may be obtained when using radiative transfer models such as Hydrolight if the modified power law variation of b_p is considered. The values provided for n_{bp} from the near infrared range, see also (Doxaran et al. 2007), are also a significant improvement on the state of knowledge, based largely on the previous findings of (Babin et al. 2003). The full relevance of the study for remote sensing problems requires further knowledge of the scattering:backscattering ratio of marine particles, often assumed as spectrally white, or alternatively similar measurements of the particulate backscattering spectrum.

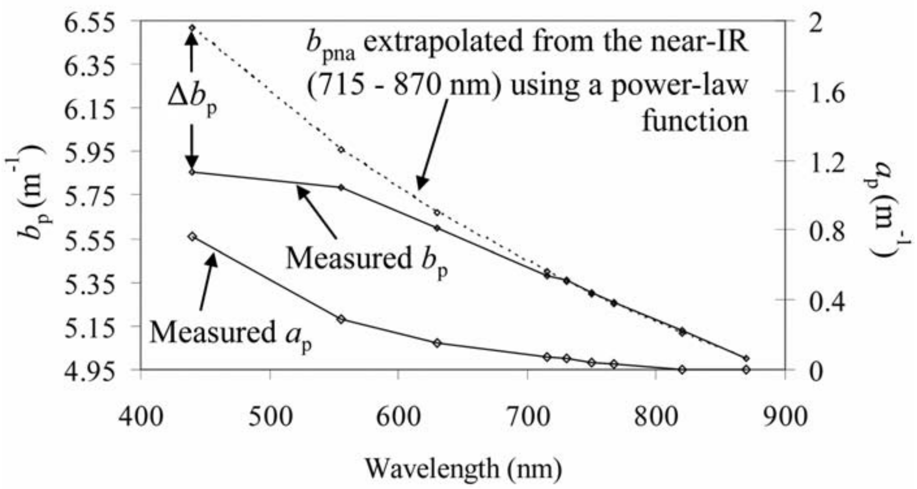


Figure 1 Typical spectral differences between measured b_p values and b_p modelled for non-absorbing particles and extrapolated from the near-IR (715–870 nm) spectral region. Reproduced from (Doxaran et al. 2009). © ASLO.

2.2.Particulate spectral scattering

In addition to the specific study described in Section 2.1 on the theoretical form for spectral variation of particulate scattering of absorbing particles, a further study was made on the variation of n as function of the size distribution and composition (refractive index) of suspended particulate matter. The power law form (1.1) for particulate scattering or particulate backscattering is assumed, either explicitly or implicitly, and usually with a "typical" constant value, n, in many remote sensing algorithms, e.g. for TSM retrieval (Nechad et al. 2010) or for turbid water atmospheric correction (Ruddick et al. 2000).

Within BELCOLOUR-2, (Astoreca et al. 2012) studied the spectral variation of particulate scattering from field data of the North Sea, laboratory experiments with mixtures of phytoplankton cultures and suspended inorganic particles and Mie theory computations.

Results show that the Southern North Sea area can be divided into three geographical zones, each one having specific biogeochemical and optical properties: Scheldt coastal zone (SCZ), Middle of the Southern North Sea (MSNS) and Thames coastal zone (TCZ). Variations in the particulate mass-specific IOPs between the three regions were observed to predominate over seasonal variations. Concentrations of organic (inorganic) particles were always higher in the SCZ (TCZ). The MSNS was characterized by a high proportion of organic particles at low concentration. The spectral exponent for particle attenuation, n, varied widely, including both positive and negative values – see Figure 2. Particle size corresponded to a power-law distribution along the coasts (especially in the TCZ). However, in the MSNS notably during the spring phytoplankton bloom, a bimodal size distribution was found with a size peak around 7μm. This anomalous size distribution explained the anomalous negative spectral slope of the particle attenuation coefficient.

One implication of the observation of spatial variability of SIOP, found also in other regions, is that remote sensing algorithms with constant SIOP will have corresponding error. This is indeed thought to be one of the major error sources for estimation of TSM. To go beyond the simple statement of SIOP variability and take account of this variability in a remote sensing algorithm with improved performance is non-trivial and is the subject of ongoing research (Brando et al. 2012). The finding of non-Junge PSD for a phytoplankton bloom and corresponding anomalous n may provide a basis for innovative techniques for remote sensing of new parameters, such as phytoplankton size, however the difficulties are significant for regions with high concentration of inorganic particulates, which will hide this effect. More promising may be the exploitation of these results in the design of in situ instruments for studying phytoplankton blooms, however more research is required to determine the robustness of such an approach (sensitivity to phytoplankton size range and noise from inorganic particulates).

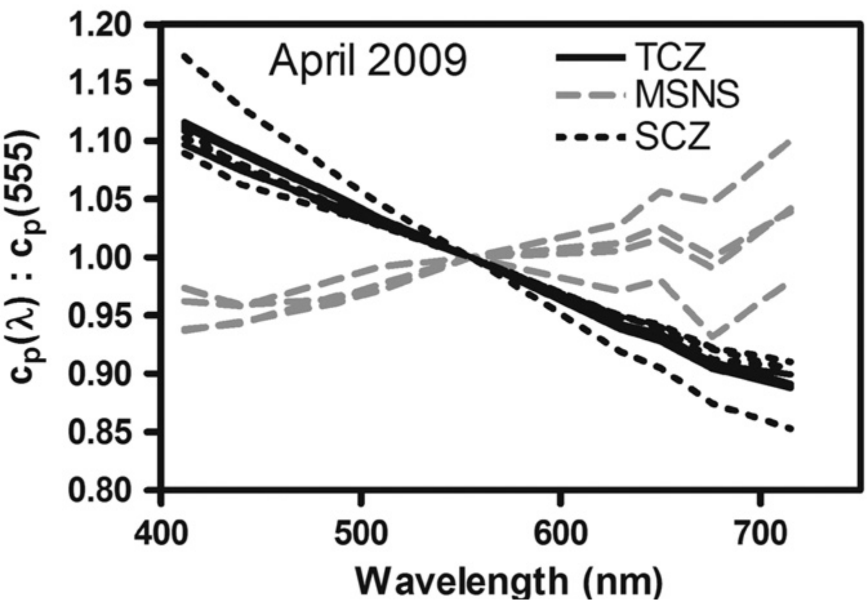


Figure 2 Spectral variations of beam attenuation coefficient, c_p , normalized at 555 nm, in April 2009 for the three geographical zones, Thames Coastal Zone (TCZ), Middle Southern North Sea (MSNS) and Scheldt Coastal Zone (SCZ). The impact of the phytoplankton bloom is evident for the MSNS spectra. Reproduced from (Astoreca et al. 2012) © Elsevier.

2.3.Particulate spectral backscattering

The studies described in Sections 2.1 and 0 have been further extended by consideration of the particulate backscatter, b_{bp} , spectral shape with corresponding power law exponent, n_{bbp} . This parameter has the added interest of being more closely related to remote sensing, where backscattering is more important than forward or total scattering, b_p . However, b_{bp} was less frequently measured than b_p , at least at the beginning of the BELCOLOUR-2 project (Dec 2006), because of the relative lack of commercial instrumentation.

Within BELCOLOUR-2, (Doxaran et al. 2010) measured the particulate backscattering coefficient from the visible to the near infrared using a specially adapted instrument to cover the near infrared range (700-900nm).

Results show significant differences for the spectral form of b_{bp} with respect to previous studies for b_p , indicating spectral variation of the scattering:backscattering ratio.

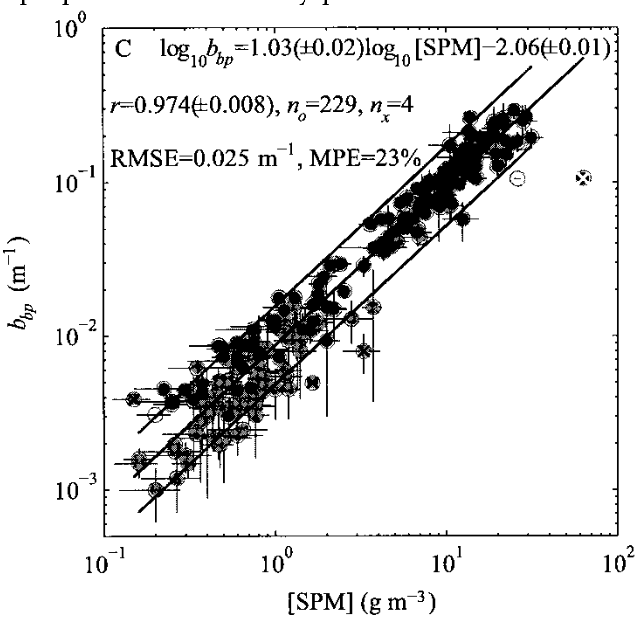
Consideration of the implication of these results awaits their full publication.

2.4.Mass-specific particulate backscattering

Whereas a remote sensor will detect the optical properties of sea water and its constituents, the sediment transport community, as users of remote sensing data, typically requires gravimetric properties, such as the mass concentration of Total Suspended Matter, S . Conversion from an optical property, usually b_{bp} , to S requires knowledge of the mass-specific backscattering coefficient, b^*_{bp} . At the beginning of the BELCOLOUR-2 project there was little knowledge of the numerical values of b^*_{bp} and its variability as function of particle size distribution and composition.

Within BELCOLOUR-2, (Neukermans et al. 2012) analysed the relationships between concentration of suspended particles represented by dry mass, S , or area, [AC], and optical properties including particulate beam attenuation (c_p), side scattering (b_s), and backscattering (b_{bp}), obtained from various coastal and offshore waters. Particle size distribution, particle size, apparent density (dry weight-to-wet-volume ratio), and particle composition were also measured as explanatory parameters.

Results show that first-order optical properties are driven by particle concentration with best



predictions of S by b_{bp} (see Figure 3) and b_s , and of [AC] by c_p . As regards second order variability, b^*_{bp} was found to vary over a factor of 3–4 and to be well correlated with particle composition, with inorganic particles having values about three times greater (b^*_{bp} = 0.012 m2 g−1) than organic particles (b^*_{bp} = 0.005 m2 g−1). The mass-specific particulate attenuation coefficient, c^*_p (= c_p : [SPM]), on the other hand, varied over one order of magnitude and is strongly driven by particle apparent density. In this data set particle size did not affect c_p^* and affected b_{bp}^* only weakly in clear (case 1) waters, despite size variations over one order of magnitude. A significant fraction (40–60%) of the variability in b_{bp}^* remained unexplained. Possible causes are the limitation of the measured size distributions to the 2–302-μm range and the effects of particle shape and internal structure that are expected to affect b_{bp} more than c_p but were not accounted for.

The implications of these findings are that algorithms for remote sensing of S that assume constant b_{bp}^*, will give errors corresponding to the observed natural variability of b_{bp}^* with a clear difference for inorganic and organic particles. Whether it is possible to design an algorithm for remote sensing of S, which exploits these findings to give different results as function of particulate organic fraction and hence improved accuracy is not yet established. Similarly the perspective raised by this study of detecting particulate organic fraction as a new remotely sensed parameter is very attractive, but requires further research for implementation in an (inverse) algorithm.

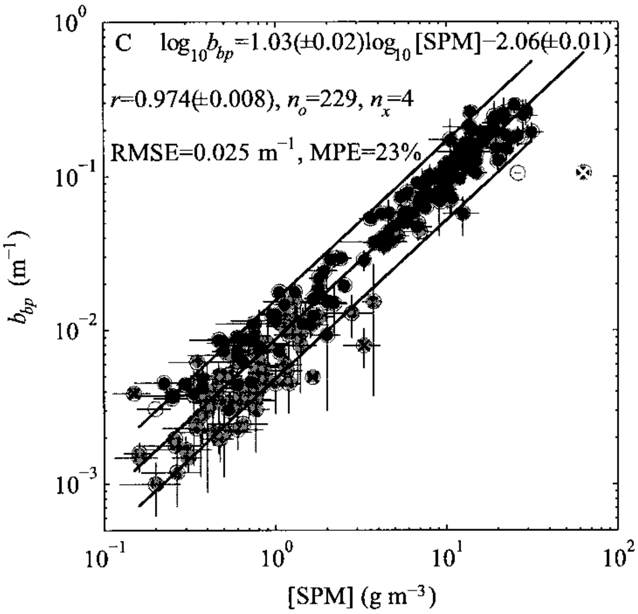


Figure 3 Scatter plots of b_{bp} vs. S [SPM]. Robust regression lines are shown in black, together with their 90% prediction bounds, equations and statistics. Reproduced from (Neukermans et al. 2012). © ASLO.

2.5. Coloured Dissolved Organic Matter

The optical properties of sea water are generally considered to be linear decomposed into contributions from pure seawater (H20 molecules), algal and non-algal particulates (considered in Sections 2.1-2.4) and Coloured Dissolved Organic Matter (CDOM). The absorption of CDOM, also termed "(dissolved) yellow substance", a_Y is generally modelled (Bricaud et al. 1981) by an exponentially decreasing function of wavelength,

$$a_Y(\lambda) = a_Y(\lambda_0)e^{-S_Y(\lambda-\lambda_0)} \qquad (1.2)$$

where S_Y is the CDOM spectral slope and λ_0 is a suitably chosen reference wavelength. Various values for S_Y have been reported in previous studies. The absorption at a reference wavelength, $a_Y(\lambda_0)$, is generally found to be correlated negatively with salinity in coastal and estuarine waters, indicating that river water (carrying the products of degradation of terrestrial vegetation) is a primary source of CDOM.

Within BELCOLOUR-2, (Astoreca et al. 2009) studied CDOM absorption in the Belgian coastal zone (BCZ) and adjacent areas including offshore waters and the Scheldt estuary.

Results showed that aCDOM(375) varied between 0.20 and 1.31 m−1 and between 0.97 and 4.30 m−1 in the marine area and Scheldt estuary, respectively. S_Y fluctuated between 0.0101 and 0.0203 nm−1 in the marine area and between 0.0167 and 0.0191 nm−1 in the Scheldt estuary. The comparative analysis of aCDOM(375) and S variations suggested different origins of CDOM in the BCZ. The Scheldt estuarine waters showed decreasing aCDOM(375) values with increasing salinity but constant S_Y of ~0.018 nm−1 suggesting a dominant terrestrial origin of CDOM. On the contrary, samples collected in the marine domain showed a narrow range of aCDOM(375) but highly variable S_Y suggesting the additional presence of autochthonous sources of CDOM. A clear distinction was made between CDOM released during the growth stage characterized by high S_Y (~0.017 nm−1) and low aCDOM(375) and the decay phase characterized by low S_Y (~0.013 nm−1) and high aCDOM(375). This observation was supported by CDOM measurements performed on pure phytoplankton cultures – see Figure 4. It is concluded that the high variability of the CDOM signature in offshore waters is explained by the local biological production and processing of CDOM.

One implication of this study is that, as for the studies of other SIOP detailed in sections 2.1-2.4, assumption of constant S_Y in a remote sensing algorithm is an approximation which does not take full account of the natural variability of this parameter. CDOM has been considered as a relevant parameter for users of remote sensing data in some coastal regions, sometimes as a proxy for salinity, but has not previously be considered for remote sensing by BELCOLOUR-2 because of the difficulties of distinguishing between particulate (detrital and mineral) yellow substance absorption and CDOM absorption in waters with high non-algal particle concentration such as those of the BCZ. Nevertheless documentation of S_Y variability and correlation, or lack of correlation, between aCDOM(375) and salinity, may be useful for ecosystem models relating PAR attenuation to TSM, salinity (CDOM) and chlorophyll a concentration (Lacroix et al. 2007). If S_Y could be effectively retrieved as an extra parameter from remote sensing, then this would, on the basis of this study, provide important extra information on the physiological state of phytoplankton in pre/post-bloom conditions. Implementation of such an approach would require solution of the difficulties of evaluating S_Y by remote sensing in the presence of non-algal particle absorption. An approach for this is described in (Brando et al. 2012).

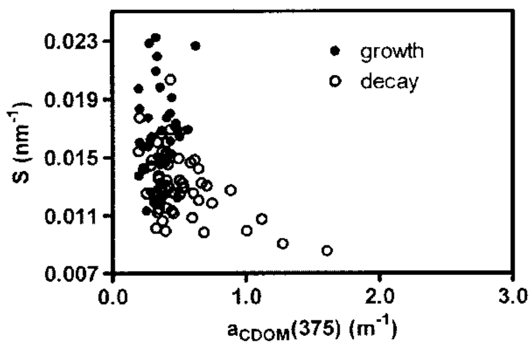


Figure 4 Relationship between S_Y and aCDOM(375) for CDOM production in cultures of *P. globosa* and *S. costatum* (including error bars). The field offshore data from the Belgian Coastal Zone is shown in grey dots. Reproduced from (Astoreca et al. 2009). © Elsevier.

2.6. Bottom reflectance

The magnitude and shape of the spectral signature of shallow waters is influenced by bottom substrates and macrophyte coverage, which complicates water quality retrieval algorithms. The degree to which the bottom signal is present in the water leaving reflectance depends on the concentrations of chlorophyll (Chl), Coloured Dissolved Organic Matter (CDOM) and Suspended Particulate Matter (SPM), respectively, the bottom depth and the bottom substrate (Brando et al. 2009; Dekker et al. 2011). This study focuses on the Spuikom, a shallow water body in Oostende, Belgium. Extensive field surveys were done: apparent optical properties were measured, water samples were analysed to derive inherent optical properties and Chl, CDOM and SPM concentrations. On three dates in-situ bottom reflectances were measured in an empty Spuikom. A large number of EcoLight radiative transfer numerical model runs were performed to generate a look-up-table with remote-sensing reflectance spectra for various water depths, bottom reflectance spectra and concentrations. The results are analysed to define when the bottom has an influence on the signal and in which conditions bottom properties can be retrieved – see Figure 5.

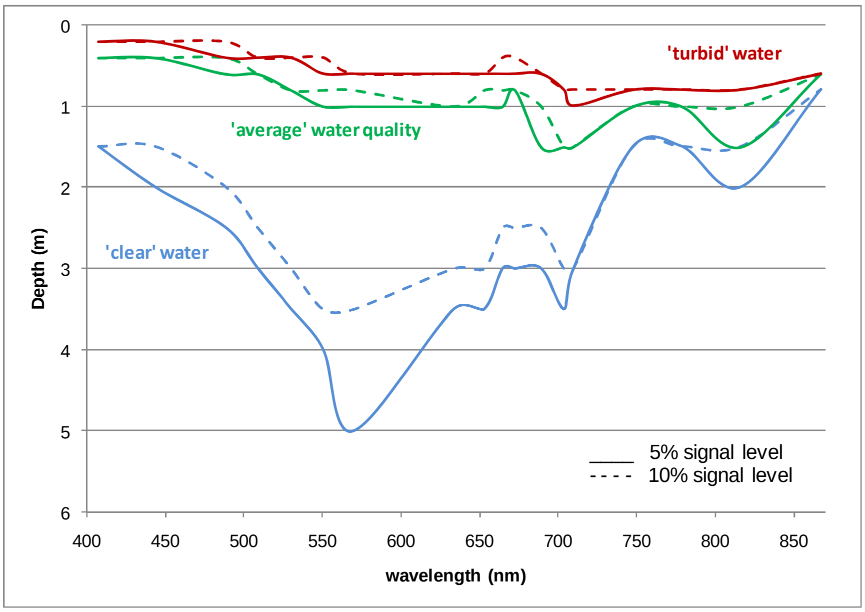


Figure 5 Model results showing the depth at which bottom reflectance affects the surface reflectance signal at the 5% or

10% level. Source: VITO.

2.7.Marine optics (other)

While Sections 2.1-2.5 describe in detail studies lead by BELCOLOUR-2 scientists on aspects of marine optics theory, the project has also contributed to a number of other studies on theoretical aspects of marine optics, including:

- A study by (Leymarie et al. 2010) using Monte Carlo simulation of the light field inside the Wetlabs AC-9 instrument used to measure absorption and scattering properties in many marine optics experiments (including those of Section 2.1, 0 2.3 and 2.4 here). This study estimated the errors that are made when measuring the absorption coefficient in highly scattering waters and proposed an improvement to the data processing method normally used.
- A study by (Tilstone et al. 2012) on the variability of SIOP, gathering data from a variety of sources, including BELCOLOUR-2, and regions, and using this data to characterise the variability into three clusters and calibrate a remote sensing algorithm, HYDROPT according to these three clusters.
- Further details on some aspects of the studies reported in Sections 0, 2.4 and 2.5 and other unpublished but related studies can be found in the PhD theses of (Astoreca 2007) and (Neukermans 2012).

3.Progress in Ocean Colour Algorithms

In Section 2 research relating primarily to inherent optical properties and theoretical aspects of marine optics, the "forward" problem, were described in detail. The present section focuses more on the remote sensing or "inverse" problem, whereby algorithms are used to estimate marine parameters of interest to users from remote sensing data, typically given via the atmospherically-corrected marine reflectance spectrum.

At the beginning of the BELCOLOUR-2 project (Dec 2006), standard products for coastal waters from the main space agencies, NASA for MODIS-AQUA and ESA for ENVISAT-MERIS, existed for chlorophyll a concentration and (MERIS only) for Total Suspended Matter. The diffuse attenuation coefficient at 490nm was available only for open ocean "Case 1" waters. There was a strong interest in algorithms for remote detection of phytoplankton species composition but the ocean colour community was still struggling to achieve good atmospheric correction and chlorophyll a retrieval for turbid coastal waters. Some studies had suggested algorithms for particular species with unique optical properties such as coccolithophores (Brown and Yoder 1994).

During the period 2006-2011, there was considerable research activity within the ocean colour community to:

a) provide new and/or improved algorithms for the base parameters, TSM and chlorophyll a and diffuse attenuation coefficient
b) provide algorithms for quality indices, confidence measures and/or uncertainty estimates for these base parameters, and
c) suggest algorithms or at least outline the way forward for developing algorithms for new parameters such as phytoplankton species composition, suspended particulate size and/or composition, etc.

The contributions of the BELCOLOUR-2 project are outlined in the following sections.

3.1.Detection of Phaeocystis globosa

While the primary parameter obtained by ocean colour remote sensing for marine biological studies is chlorophyll a concentration, there is considerable user interest in going beyond just chlorophyll *a* and obtaining information on the phytoplankton species composition. As an example, in Belgian waters the prymnesiophyte *Phaeocystis globosa*, referred hereafter as Phaeocystis, forms large ungrazed colonies (up to 3 mm diameter) that accumulate in the water and create, under windy conditions, thick layers of foul-smelling foam on beaches. This species is considered as harmful (but not toxic) and monitoring is required as an indicator of eutrophication for reporting of water quality under the European Union Water Framework Directive and the Marine Strategy Framework Directive. A first approach to monitoring would typically be to combine remotely sensed phytoplankton biomass (via the proxy chlorophyll a) with in situ measurements of phytoplankton species composition. However, the direct remote sensing of *Phaeocystsis* and/or diatoms, the other main component of the phytoplankton community n Belgian waters, is a long-term objective. A review of harmful algae bloom detection by satellite was made in the previous BELCOLOUR-1 project by (Ruddick et al. 2008).

Within BELCOLOUR-2, following on from previous work (Astoreca et al. 2005; Astoreca et al. 2006) in the BELCOLOUR-1 project, (Astoreca et al. 2009) measured the absorption properties of *Phaeocystis* and diatoms in the Southern North Sea and on laboratory cultures and used this information to develop an algorithm for direct remote detection of *Phaeocystsis*.

Results showed that the main spectral difference between *Phaeocystis* and diatoms was observed at 467 nm due to the absorption of the pigment chlorophyll c3 only present in *Phaeocystis*.. A *Phaeocystis* -detection algorithm was then proposed to retrieve chlorophyll c3 using either total absorption or water-leaving reflectance field data. Contamination of results by non-algae particle absorption were minimised by use of an exponential baseline approach between the wavelengths 450nm and 480nm. Application of this algorithm to absorption and hyperspectral reflectance data from *Phaeocystis*-dominated natural communities showed positive results. Comparison with pigment concentrations and cell counts suggests that the algorithm can flag the presence of *Phaeocystis* and provide quantitative information above a chlorophyll c3 threshold of 0.3 mg m−3 equivalent to a cell density of 3 × 106 cells L−1.

The **implications** of this study are that the systematic difference of absorption between *Phaeocystsis* and diatoms, because of the presence of the chlorophyll c3 pigment in *Phaeocystsis* only, could be used to detect *Phaeocystsis* at least when present in very high concentrations. The algorithm was applied successfully to sea level hyperspectral reflectance measurements, but not (yet) to satellite measurements because of lack of an appropriate sensor. Implementation of such an algorithm in practice will require a hyperspectral remote sensor or at least wavelengths such as 450nm, 467nm and 480nm as well as an atmospheric correction algorithm that preserves, without distortion, the marine reflectance spectrum in the range 450-480nm.

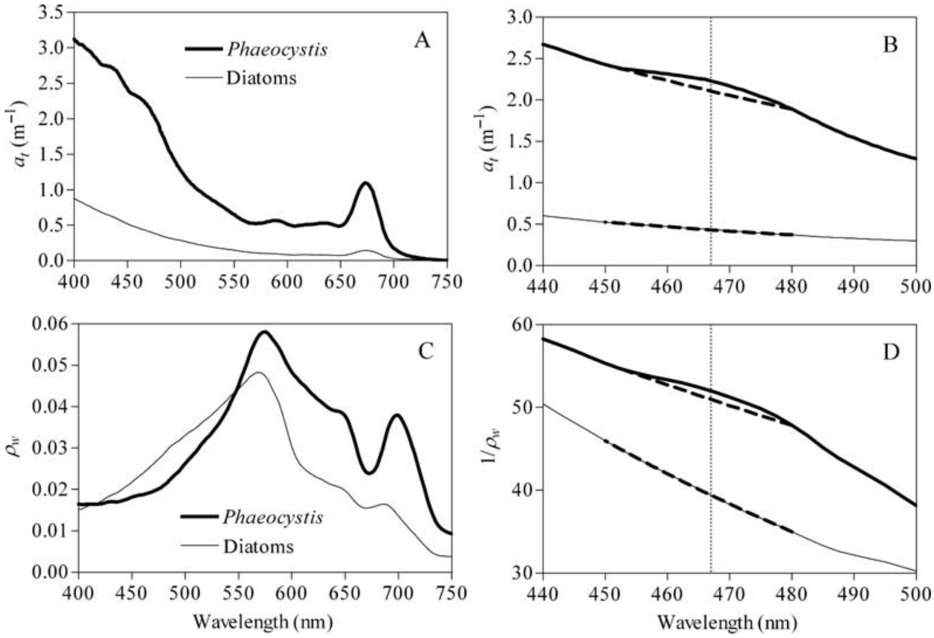


Figure 6 Total absorption spectra (A) and water-leaving reflectance (C) measured at sea for Phaeocystis-dominated (10 May 2004) and diatom-dominated (30 June 2005) samples. Enlargement of the region 440–500 nm to show the principle of the algorithm based on absorption (B) and reciprocal of water-leaving reflectance for the spectra shown in (C) with enlargement of the region 440–500 nm (D). The baselines obtained by exponential interpolation between 450 and 480 nm are superimposed as bold dotted lines (B and D). The 467 nm feature is shown as a vertical dotted line. Reproduced from (Astoreca et al. 2009). © The authors (Creative Commons Attribution Non-Commercial License).

3.2.Detection of Noctiluca scintillans

Blooms of *Noctiluca scintillans* a heterotrophic, bloom forming dinoflagellate blooms, are often observed as reddish patches in Belgian waters in June-July in calm weather. In some regions of the world blooms of *Noctiluca scintillans* have been linked to massive fish and marine invertebrate kills possibly via generation of high levels of ammonia. These blooms have not been shown to be harmful in Belgian waters, but their role in clearing the water of other plankton is thought to be an important element of the trophic chain (Daro et al. 2006).

In BELCOLOUR-2, (Van Mol et al. 2007) studied *Noctiluca scintillans* by laboratory absorption and seaborne and airborne field reflectance measurements (Figure 7) and developed an algorithm for remote sensing of this species.

Results showed that intense blooms of *Noctiluca scintillans* can be detected, distinctly from phytoplankton blooms and non-algal particles, by an algorithm based on a combination of a high reflectance threshold with a condition of sharp increase in reflectance in the range 520-580 nm.

The **implication** of these results is that remote sensing of intense blooms of *Noctiluca scintillans* is feasible from optical remote sensing. Wavelengths requirements are not severe, since an algorithm based only on bands at 530nm and 550nm was tested, but other wavelength pairs in the range 520-580nm may also be suitable. The main limitation for application to satellite data is likely to be the requirement for spatial resolution sufficient to capture patchy blooms. The application of this algorithm to other regions also requires further clarification, particularly if optical properties are related to gut content.

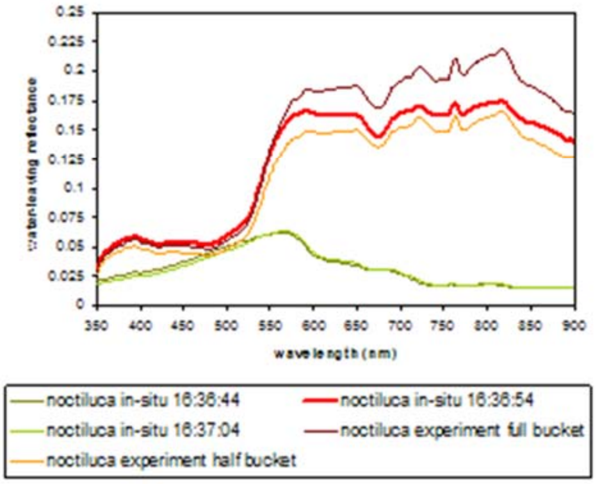


Figure 7 Water-leaving reflectance measured on 29 June 2005 in the middle of the Noctiluca patch (red), just before and after entering the patch (green) and measured on board in a bucket full (mauve) and half full (orange) with *Noctiluca scintillans*. Reproduced from (Van Mol et al. 2007). © EARSEL.

3.3.Estimation of Total Suspended Matter (satellite)

At the beginning of BELCOLOUR-2 there was a strong interest from sediment transport modellers for data on total suspended matter concentrations and some prior studies (Fettweis et al. 2007) exploiting such data from ocean colour remote sensing in the Southern North Sea using a preliminary single band algorithm (Nechad et al. 2003) for estimation of Total Suspended Matter (TSM) similar in concept to prior work on TSM estimation from AVHRR (Stumpf and Pennock 1989). Within the ocean colour community more generally there was a similar interest from scientists in a few turbid coastal regions (Eleveld et al. 2004), but TSM was available as a standard product only from MERIS and not from SeaWiFS or MODIS. A review of the state of the art for TSM estimation was made early in the BELCOLOUR-2 project by (Ruddick et al. 2008).

In BELCOLOUR-2, (Nechad et al. 2010) developed the theoretical basis for single bands TSM retrieval algorithms. They used in situ marine reflectance and TSM measurements for calibration and satellite-derived marine reflectance and concurrent in situ TSM measurements for validation (see

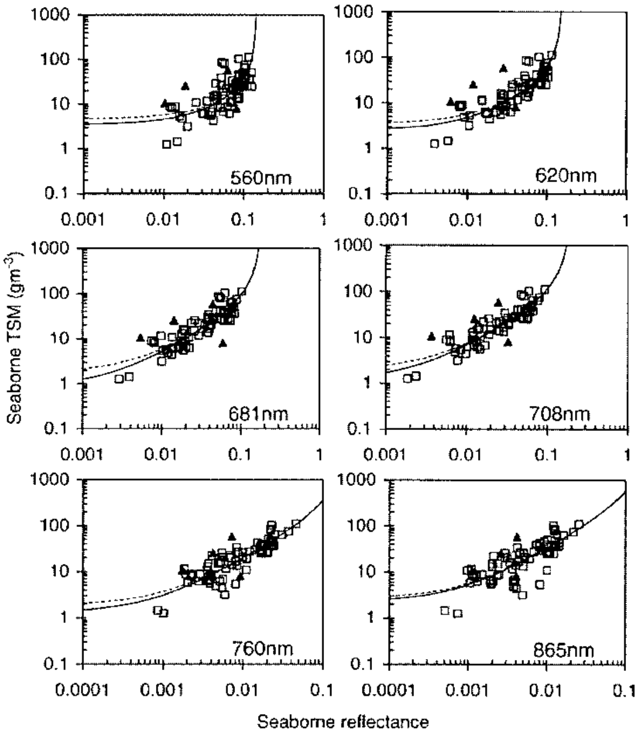


Figure 8).

Theoretical results show that use of a single band provides a robust and TSM-sensitive algorithm provided the band is chosen appropriately. Results include a generic algorithm for TSM estimation in turbid waters and calibration coefficients to use this algorithm with MERIS, MODIS and SeaWiFS but also a calibration table for use with any ocean colour sensor with a band in the range 600-900nm. Two versions of the algorithm are considered: one which gives directly TSM from reflectance, the other uses the reflectance model of Park and Ruddick (2005) to take account of bidirectional effects. Validation of this algorithm for MODIS and MERIS retrieved reflectances with concurrent in situ measurements gave the lowest relative errors (less than 40%) in TSM estimates for MODIS bands 667 nm and 678 nm and for MERIS bands 665 nm and 681 nm. Consistency of the approach in a multisensor context (SeaWiFS, MERIS, and MODIS) was demonstrated both for single point time series and for individual images.

The **implication** of this study is that a consistent and generic multi-sensor theoretical basis is available for TSM estimation from SeaWiFS, MODIS and MERIS but also from a wide range of other past, present and future remote sensors, e.g. CZCS, AVHRR, SPOT, LANDSAT, ASTER, GOCI, etc. Considerations of algorithm performance suggest that, while a single band approach is robust and accurate, the wavelength chosen for retrieval could be varied as function of turbidity (or TSM or marine reflectance) in order to achieve an optimal signal:noise ratio and algorithm sensitivity. Such a adaptive single band TSM retrieval approach has been proposed by (Shen et al. 2010) and is being further investigated by BELCOLOUR-2 partners.

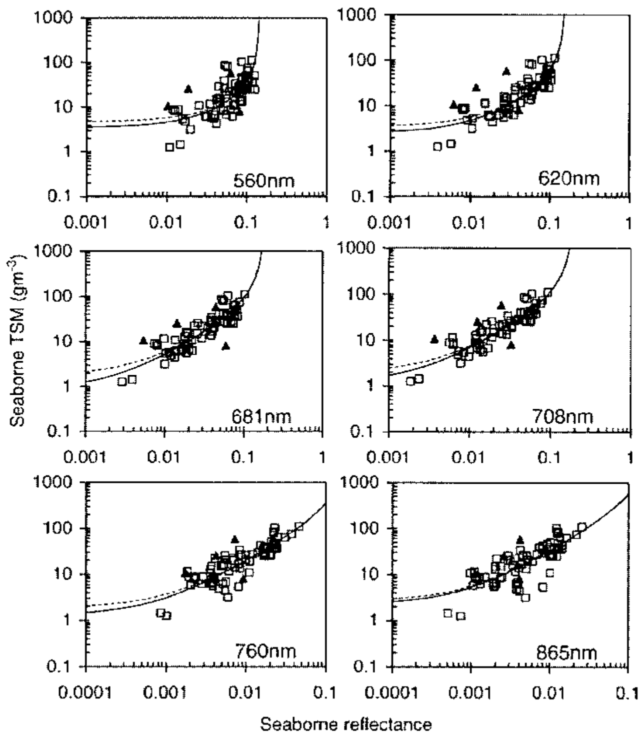


Figure 8 Non-linear regression curve for MERIS at 6 selected bands (560, 620, 681, 708, 760 and 865 nm), superimposed on the scatter plot of 72 TSM versus reflectance data (squares). The dashed lines show the regression analysis curves resulting from the use of the 72 observations and the solid lines come from regression analysis applied to 68 observations (dropping out the 4 outliers drawn as filled symbols). Reproduced from (Nechad et al. 2010) © Elsevier.

3.4.Estimation of Total Suspended Matter (airborne)

At the beginning of the BELCOLOUR-2 project, airborne remote sensing of TSM was also a developing application, with a previous study documented by (Sterckx et al. 2007). Airborne remote sensing was considered as better adapted to the remote sensing of estuarine and inland waters, where spatial resolution requirements are more severe and met only infrequently by satellite sensors such as SPOT and LANDSAT.

In BELCOLOUR-2, (Knaeps et al. 2010) measured marine reflectance and TSM concentration in situ for various seasons, years and tidal phases and processed airborne imagery (AHS) for the Scheldt Estuary. Various functional forms (single band, band difference and band ratios) were tested for TSM algorithms using water reflectance as input.

Results showed best correlations for exponential relationships between band ratios and TSM concentration. The best algorithms were validated using airborne imagery acquired at different moments of the tidal cycle. Finally a ratio algorithm based on bands 710nm/596nm was used to derive a TSM map of the Schledt River from the AHS airborne sensor (Figure 9).

The implications of this study are that TSM can be mapped at high spatial resolution from airborne remote sensing with a single algorithm that showed good performance over a range of conditions. The diversity of approaches for TSM retrieval adopted both within the BELCOLOUR-2 project (single band, band difference, band ratio) and the ocean colour community as a whole (as BELCOLOUR-2 plus multispectral inversions) suggests that there is not yet consensus on an optimal approach.

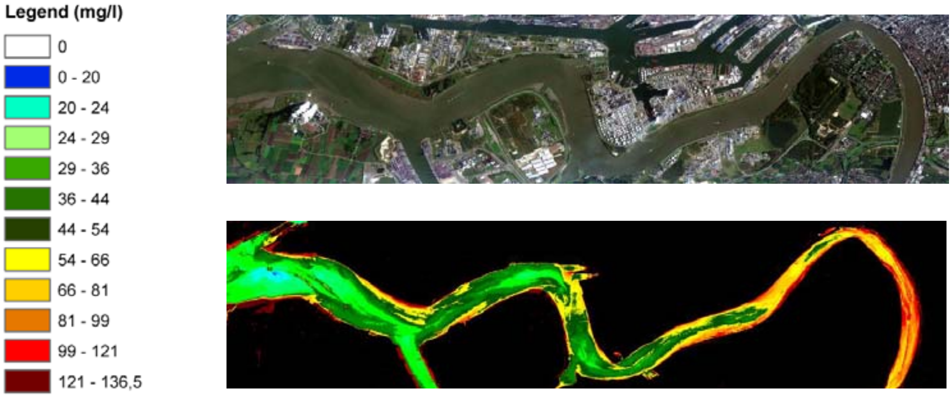


Figure 9 (top) Hyperspectral image of the Scheldt river, 6 June 2009, 10:03 UTC, (bottom) SPM concentration map of the Scheldt River. © The authors (Creative Commons Attribution Non-Commercial License).

3.5.Atmospheric correction and estimation of TSM from SEVIRI

At the beginning of the BELCOLOUR-2 project, optical remote sensing of marine parameters had never been attempted from a geostationary platform. Polar-orbiters such as SeaWiFS, MODIS and MERIS were the mainstream and the geostationary orbit was generally considered as too challenging for ocean colour remote sensing because of the difficulties of meeting the signal:noise requirements of ocean colour at this much higher orbit. The difficulty of atmospheric correction at high viewing zenith angles was also considered as a major obstacle. The main space agency plans for optical remote sensing from geostationary platforms were limited to the detection of clouds, which are a much brighter target than oceans.

In **BELCOLOUR-2**, (Neukermans et al. 2009) developed an atmospheric correction algorithm for the SEVIRI sensor onboard the METEOSAT Second Generation (MSG) geostationary platform. They also calibrated a TSM retrieval algorithm for the red (0.6μm) band of this sensor using seaborne measurements of TSM and marine reflectance. They processed SEVIRI data for the Southern North Sea at 15 minute temporal resolution for 35 consecutive days in summer 2006. In a follow-up study, (Neukermans et al. 2012) improved the methodology for atmospheric correction, proposed a method for improving spatial resolution by use of the HRV (High resolution Visible) band and added algorithms for estimation of turbidity and the vertical attenuation coefficient of downwelling PAR irradiance (KdPAR). They further processed a 2 year archive of SEVIRI imagery and compared results for turbidity and KdPAR with in situ measurements from moored buoys (Smartbuoys) in the southern North Sea.

Results demonstrated that mapping of TSM in the Southern North Sea is feasible with SEVIRI for turbid waters, though with considerable uncertainties in clearer waters. TSM maps obtained from SEVIRI were well correlated with similar maps obtained from MODIS AQUA. During cloud-free days, SEVIRI measured the high frequency dynamics of TSM, not available from polar-orbiters such as SeaWiFS, MODIS and MERIS. Validation of against moored buoy data, with over 1000 matchups, gave 80% of SEVIRI-derived turbidity and KdPAR within 53% and 39% of the in situ data respectively. Moreover, SEVIRI data was demonstrated to pick up the diurnal variability of these parameters (Figure 10), with phasing of the maximum turbidity with an average phase difference between satellite and in situ data of 11 minutes and 23 minutes for turbidity and KdPAR respectively.

The **implication** of this study is that optical remote sensing of marine parameters is feasible from the geostationary orbit. Here this was demonstrated only for TSM, turbidity and PAR attenuation because of the spectral and radiometric limitations of the SEVIRI sensor, which was clearly not designed for this purpose. Remote sensing of chlorophyll a for the open oceans would be an additional challenge, because of the more severe requirements for an accurate atmospheric correction for blue and green bands and for detection of darker targets. On the other hand, a gesotationary sensor actually designed for ocean colour applications may meet such challenges. The higher frequency of acquisition made possible by the geostationary orbit (imagery every hour or less, compared to approximately every day from polar orbiters) offers enormous potential for future applications of ocean colour remote sensing. The probability of obtaining at least one image per day for a region in periods of scattered clouds is greatly increased (Mazeran and Meskini 2008). The possibility of measuring higher frequency processes (tidal variability, vertical migration), previously inaccessible to ocean colour remote sensing, becomes feasible. Since publication of the study of (Neukermans et al. 2009), the successful launch and processing of data from the geostationary sensor, GOCI, by the Korean Ocean Satellite Center (KOSC) has dramatically changed perceptions of the feasibility of geostationary ocean colour remote sensing. This may lead to acceleration of the plans of the European Space Agency (GEO-OCULUS/OCAPI/HOCI) and/or of NASA (GEOCAPE) to launch similar missions, although these plans are still many years or possibly more than a decade away from fruition.

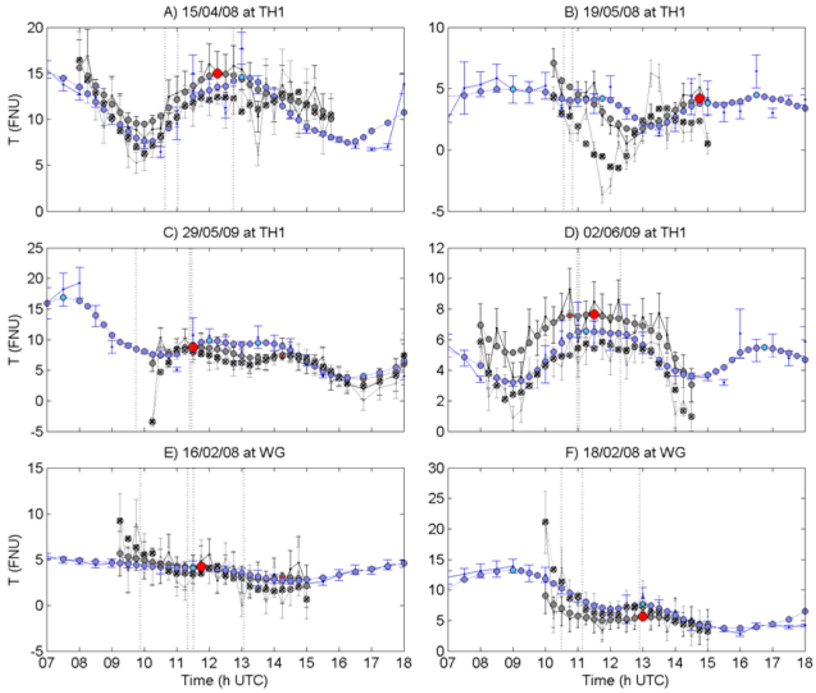


Figure 10 Time series of turbidity, T, for various locations in the Southern North Sea obtained from SEVIRI and SmartBuoys. SEVIRI T data from the VIS06 and HRV bands with their uncertainty are shown by the black and grey error bars, respectively. Temporally smoothed data series for VIS06 (O) and HRV (⊗) T products are shown in grey, with global (big red dot) and local (small red dots) maxima. SmartBuoy T and its uncertainty is shown by the blue error bars, while the temporally smoothed data series is shown by blue circles with local maxima highlighted in cyan. Grey vertical dotted lines represent data availability from MODIS Aqua/Terra and MERIS ENVISAT. Reproduced from (Neukermans et al. 2012). © Elsevier.

3.6. Estimation of Turbidity

While sediment transport modellers tend to request TSM, a gravimetric parameter, there is a growing interest in the water quality community in turbidity, an optical parameter that can be measured by remote sensing. This interest is driven by the European Union's Marine Strategy Framework Directive (European Union 2008) which lists turbidity as a required monitoring parameter. To avoid confusion with different understandings of the meaning of "turbidity", the ISO definition of turbidity (ISO 1999) is used here, based on the principle of side-scattering at 860nm with respect to the chemical standard Formazine and expressed in Formazine Nephelometric Units (FNU). There is a strong correlation between turbidity and other parameters such as TSM concentration, reflectance, backscatter, transparency and beam and diffuse attenuation. Turbidity, as a remotely sensed parameter, received less attention than TSM prior to BELCOLOUR-2. However, as an optical parameter rather than a gravimetric parameter, it is more relevant than TSM for environmental applications regarding water transparency and light availability for primary production. Also remote sensing of turbidity is better adapted to optical remote sensing than TSM because TSM retrieval uncertainties associated with natural variability of mass-specific particulate backscatter are not relevant to turbidity.

In BELCOLOUR-2, (Nechad et al. 2009) developed a turbidity retrieval algorithm following the same theoretical basis as for TSM (Nechad et al. 2010). Seaborne measurements of marine reflectance and turbidity were used to calibrate this algorithm. Validation was carried out using an independent set of seaborne measurements of turbidity and reflectance.

Results include a table with calibration coefficients for a turbidity algorithm for any single wavelength in the range 600-850nm (see Figure 11). Validation for turbidity retrieval at 681nm (corresponding to a MERIS band) was found to give low relative error (less than 35%).

The **implication** of this study is that a consistent and generic multi-sensor theoretical basis is available for turbidity estimation from SeaWiFS, MODIS and MERIS but also from a wide range of other past, present and future remote sensors, e.g. CZCS, AVHRR, SPOT, LANDSAT, ASTER, GOCI, etc. This may be of particular interest for countries in Europe faced with the obligation of monitoring turbidity in the framework of the Marine Strategy Framework Directive. As for TSM estimation, the optimal choice of wavelength for retrieval may depend on turbidity itself. In the case of MERIS, the 681nm band is expected to give good performance for the range of turbidity encountered in this study, at least for cases where no significant fluorescence affects the marine reflectance. In conditions where fluorescence is important (high chlorohyll, low turbidity) compared to scattering at 681nm, other bands can be chosen from the generic table provided by this study.

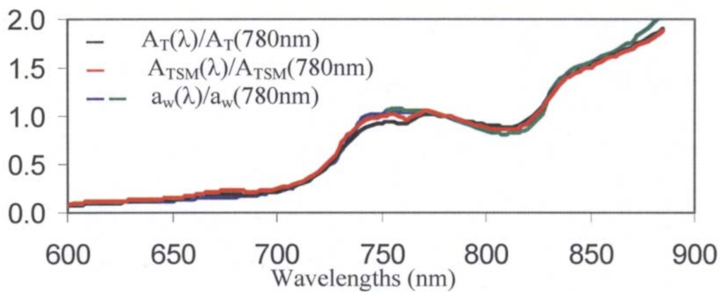


Figure 11 The calibration coefficient for turbidity (black line), A_T, and TSM (red), A_{TSM}, algorithms for wavelengths ranging from 600nm to 885nm and normalized at 780nm superimposed with the pure water absorption normalised at 780nm using data from (Kou et al. 1993) for $\lambda > 751$nm (green) and data from (Buiteveld et al. 1994) for 500nm $< \lambda <$

800nm(blue). Reproduced from (Nechad et al. 2009). © SPIE.

3.7.Estimation of turbidity in extremely turbid waters

The algorithm of (Nechad et al. 2009) established a theoretical basis for estimation of turbidity in moderately turbid waters. However, there is a growing interest from users of remote sensing data to push existing algorithms into new, more extreme concentration ranges,. For turbidity, such an interest arises for the world's most turbid river plumes (Changjiang, La Plata, Amazon, Gironde, etc.) as well as a larger number of extremely turbid estuaries and inland waters (Scheldt, Lake Taihu, Ijsselmeer, etc.). For such regions, TSM can reach a few hundred g/m3 and the near infrared bands proposed by (Nechad et al. 2010) become less sensitive to TSM (or turbidity) variation.

In BELCOLOUR-2, (Dogliotti et al. 2011a) extended the single band turbidity retrieval approach of (Nechad et al. 2009) to the extremely turbid waters of the estuary and plume of the Rio de La Plata between Argentina and Uruguay. They achieved this by using the MODIS near infrared and short wave infrared 858nm and 1240nm bands A partial atmospheric correction was performed based on a Rayleigh correction and a band difference approach for turbidity estimation, thus avoiding the problems associated with a full atmospheric correction in extremely turbid waters.

The **results** showed that turbidity and TSM can indeed be estimated in such extremely turbid waters by the use of NIR and SWIR bands and with a simple Rayleigh-corrected reflectance band differences. The maps obtained were found to be consistent with known values and their spatial distributions of turbidity and TSM in the region (Figure 12).

The **implications** of this study are that TSM and turbidity estimation can be made by optical remote sensing for extremely turbid waters, provided that suitable NIR and SWIR spectral bands are available as is the case for MODIS-AQUA. Similar studies in Chinese waters (Wang et al. 2011) confirm the importance of SWIR bands for extremely turbid waters. Such studies are starting to influence the design of future ocean colour sensors and, for example, a 1020nm band has been included for the Sentinel-3/OLCI sensor that was not present on MERIS.

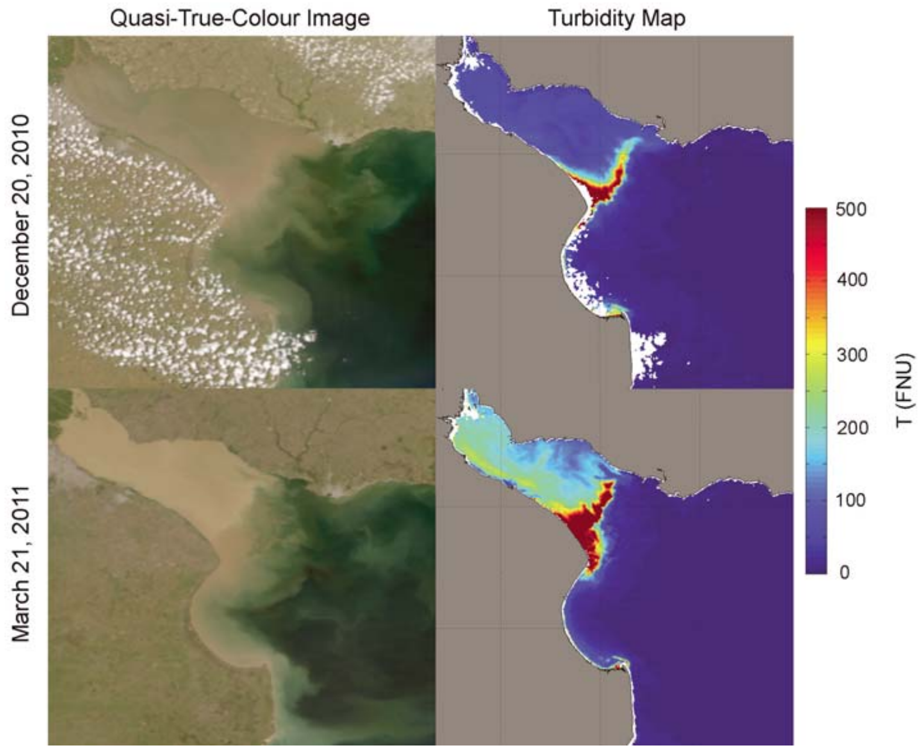


Figure 12 MODIS-Aqua Quasi-True-Colour image (left column) and Turbidity map (right column) for La Plata River Estuary on December 20, 2010 (upper panels) and March 21, 2011 (lower panels). Reproduced from (Dogliotti et al. 2011a). © EARSEL.

3.8.Marine reflectance in the Short Wave Infrared

At the beginning of the BELCOLOUR-2 project, the Short Wave Infrared (SWIR: 1-3μm) range was not considered as suitable for ocean colour remote sensing because marine reflectance was thought to be negligible in this range. A first exploitation of SWIR bands for ocean colour probably comes from (Wang and Shi 2005) who developed an atmospheric correction algorithm for MODIS based on the 1240nm and 1640nm bands, assuming zero marine reflectance for those bands.

In BELCOLOUR-2 (in collaboration with the MICAS project), (Knaeps et al. 2012) made measurements of marine reflectance in the SWIR range for the Scheldt Estuary using the ASD spectroradiometer and corresponding measurements of TSM and turbidity on water samples. Airborne imagery from the APEX sensor was also processed and numerical simulations were made with the Hydrolight model.

Results from in situ measurements (Figure 13), airborne imagery and numerical simulations show that marine reflectance is not zero at 1020nm for extremely turbid waters and that the black pixel assumption, typically made for atmospheric correction algorithms, is thus not valid in these conditions. A high correlation was observed between the water-leaving reflectance at 1020 and 1050 nm and TSM concentration.

The **implications** of this study are that non-zero marine reflectance at 1020nm needs to be considered for the OLCI atmospheric correction algorithm and that this band may contain useful information for the remote sensing of turbidity or TSM in extremely turbid waters. More generally, this study provides a theoretical and in situ measurement basis for further exploitation in extremely turbid waters of the SWIR bands of existing, planned and yet to be designed ocean colour sensors.

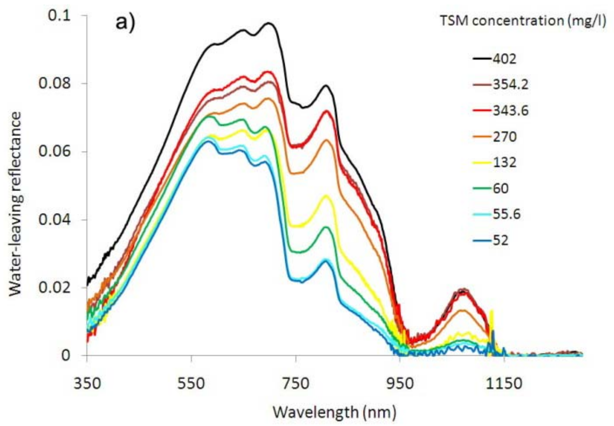


Figure 13 Water-leaving reflectance measured in July 2010. Corresponding TSM concentrations are indicated in mg/L. Reproduced from (Knaeps et al. 2012). © Elsevier.

3.9.Geostatistical analysis – cloud-filling and more

At the beginning of the BELCOLOUR-2 project, there was a strong interest in using TSM data from ecosystem modellers requiring continuous information on light attenuation for the light forcing component of 3D models to simulate eutrophication and phytoplankton dynamics. In an early study by (Lacroix et al. 2007) a four-season TSM climatology derived from SeaWiFs was used, but it was clearly recognised that much of the temporal variability of the ambient light field, and hence processes such as light triggering of the spring bloom, were missing from this low frequency dataset. The usage of TSM fields with higher temporal resolution was hampered by the large percentage of missing data owing to clouds and, to a lesser extent, data considered as of suspect quality. Temporal merging of ocean colour data at that time was essentially limited to simply multitemporal averaging (e.g. weekly/monthly), possibly with use of last-available data or climatological data in the case of no data being available during the averaging period.

In BELCOLOUR-2 (and the associated RECOLOUR project) (Sirjacobs et al. 2008; Sirjacobs et al. 2011) applied a Data Interpolating Empirical Orthogonal Function (DINEOF) to a four year time series of sea surface temperature (SST), TSM and chlorophyll a data for the Southern North Sea and English Channel from the MODIS-AQUA and MERIS sensors. The method was first validated by comparing reconstructed data for 3 dates below 2 artificial clouds with the excluded data and then, in a follow-up study (Nechad et al. 2011), by comparison of reconstructed data with in situ measurements from autonomous buoys.

Results showed that 93.5% (CHL), 97% (TSM) and 98% (SST) of the variability of the original dataset could be reconstructed by the DINEOF technique. Complete weekly and monthly averaged climatologies, suitable for use with ecosystem models, were derived from regular daily reconstructions. Error maps associated with every reconstruction were produced. These error maps allowed automatic detection of outliers in the reconstuctued fields, thus indicating unusual or suspicious data points compared to the global dynamics of the dataset (Figure 14). These outlier data were attributed to a variety of factors (undetected cloud edges, haze areas, contrails, cloud shadows). Validation with in situ data showed differences generally less than 40% in turbid waters with a variety of causes including imperfect atmospheric correction, imperfect TSM retrieval, in situ measurement issues and reconstruction errors.

The **implications** of these studies are that the DINEOF approach can facilitate the generation of complete cloud-free fields of data, as required for example for forcing ecosystem models. Also the new (for ocean colour) approach of identifying outliers has the potential for improving the automatic quality control of standard processing chains, such as those implemented in space agencies distributing ocean colour data.

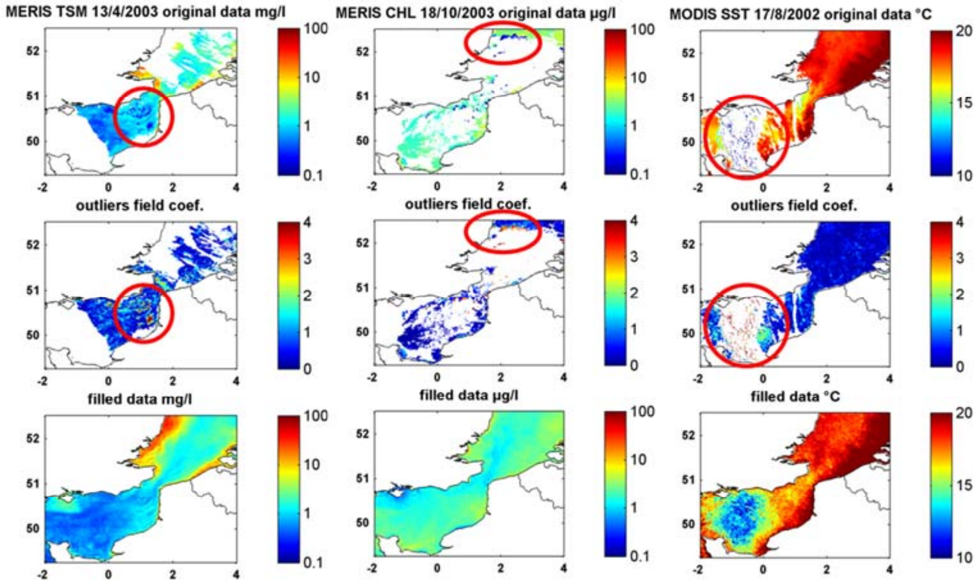


Figure 14 Illustration of original fields, outliers and reconstructions maps for: MERIS TSM on 13/04/03 with probable undetected haze, MERIS CHL on 18/10/03 with clear outliers at cloud edges, MODIS SST on the 17/08/02 with numerous outliers spread throughout a large clouded area. Reproduced from (Sirjacobs et al. 2011). © Elsevier.

3.10.Algal bloom detection

At the beginning of the BELCOLOUR-2 project there was a user interest in various European countries in detecting algal blooms, particularly harmful blooms where real-time information can affect the management of such events. The NOAA service for the West Florida shelf (Stumpf 2001) was an early example of an operational algae bloom detection service based partially on satellite data.

In the BELCOLOUR-2 project (Park and Ruddick 2007; Park et al. 2010) developed a method for detection of an algal bloom from MODIS and MERIS data based on when chlorophyll a concentration exceeds predefined threshold map, calculated on a pixel-by-pixel basis from the percentile 90 of chlorophyll data from previous years. As support for this method the MODIS and MERIS chlorophyll data were compared.

Results showed good agreement of MODIS and MERIS data in case 1 waters, but significant differences in coastal waters including turbid areas. A relationship between the water-leaving reflectance at 667nm and Chl for case 1 waters was used to eliminate pixels where MODIS Chl retrieval is contaminated by backscatter from inorganic suspended matter. The use of the precalculated threshold map gave robust performance for the study region. This method avoids the difficulties associated with specifying a single threshold concentration for the whole region (not taking account of regional differences in bloom magnitude).

The implications are that this pixel-by-pixel threshold approach is a good way to detect the high biomass algal blooms occurring once or a few times per year (according to the region). This does not, however, correspond precisely to the general definition of an algal bloom as a rapid *increase* in algal biomass rather than a *high* biomass. The use of satellite chlorophyll to detect increase (time variation) is hampered particularly in turbid waters and particularly at the early stages of a bloom by limitations on detection of low concentrations. Although originally intended with near real-time applications in mind, the same method can be used to estimate the *timing* of the spring bloom, and study its interannual variability, causes (light availability, nutrients) and impacts (on subsequent trophic dynamics potentially all the way to the higher predators).

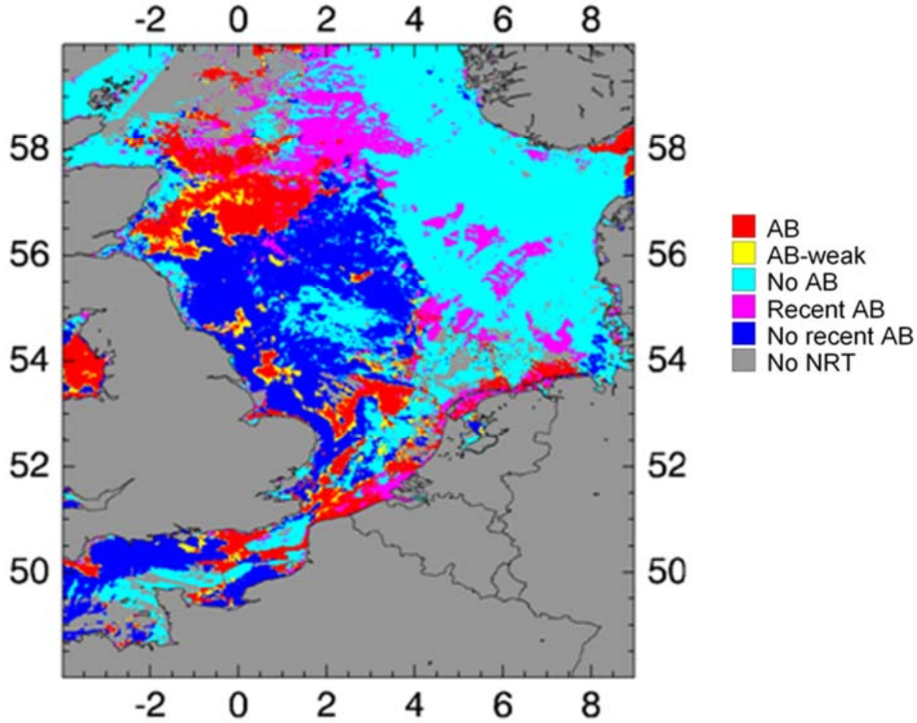


Figure 15 An example of an AB flag image of 18 April 2007 for the North Sea, showing

classification of pixels based on previous day's imagery and the previous 7 days' classification. Reproduced from (Park and Ruddick 2007; Park et al. 2010). © Taylor and Francis.

3.11.Atmospheric correction – adjacency effects

At the beginning of the **BELCOLOUR-2 project** there was a growing interest in exploitation of optical remote sensing data for waters close to land, e.g. the European Union Water Framework Directive required monitoring for inland waters and for coastal waters, but only within 1 nautical mile of the coast. While the quality of chlorophyll products in coastal waters was generally improving these very nearshore waters present (still today) severe difficulties for remote sensing: a) Very nearshore waters are often very turbid making both atmospheric correction and chlorophyll retrieval more difficult, b) In inland and very nearshore waters, reflectance from the sea bottom if more frequently significant (and problematic for remote sensing), c) When a remote sensor views a water pixel target close to land, some light scattered by the land may also be captured because of a too-broad point response function of the sensor ("instrument straylight") or because of forward scattering of light in the atmosphere ("environmental straylight" or "adjacency effect"). The latter effect, termed hereafter "adjacency" is particularly severe for dark water targets close to bright land targets (e.g. clear waters of deep fjords or many inland waters) and especially when there is vegetation on land combined with atmospheric correction algorithms

(Gordon and Wang 1994) that estimate aerosol properties from near infrared bands. Some prior theoretical work (Reinersman and Carder 1995; Santer and Schmechtig 2000) was available at the beginning of the BELCOLOUR-2 project, but there were no operational implementations of adjacency correction algorithms.

In BELCOLOUR-2 (Sterckx et al. 2011) presented a method for the detection and correction of water pixels affected by adjacency effects. The approach is based on comparison of spectra with the near-infrared similarity spectrum (Ruddick et al. 2006). The approach has the advantage that it requires no a priori assumptions on the sediment load or related reflectance values in the near infrared and can therefore be applied for turbid waters. The approach was tested on hyperspectral airborne data (CASI, AHS) acquired above coastal and inland waters at different flight altitudes and under varying atmospheric conditions.

Results obtained suggest that adjacency effects can be very significant even at 1 km flight altitudes and are effectively detected and corrected by the method.

The **implication** of this study is that it could form the basis of an operational procedure for the detection and correction of adjacency effects for sensors such as MERIS. Indeed problems associated with the processing of MERIS data in nearshore waters have been approached both by a refined version of the method described here, branded "SIMEC" (Knaeps et al. 2010) and by the ESA-sponsored "ICOL" approach (Santer and Zagolski 2008). Both methods are evolving and being subjected to wider testing.

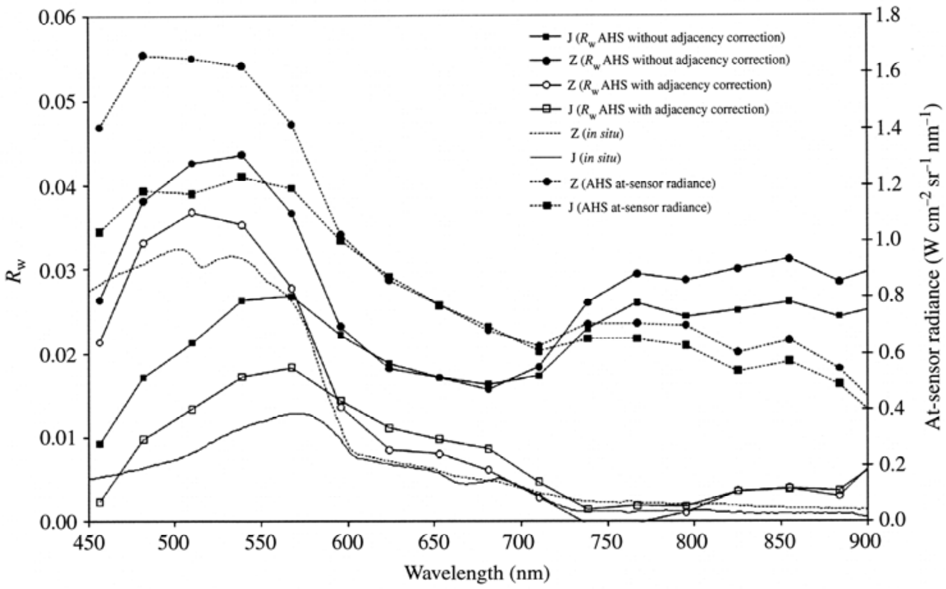


Figure 16 Water-leaving reflectance spectra before and after adjacency correction and averaged in situ water-leaving reflectance. Reproduced from (Sterckx et al. 2011). © Taylor and Francis.

3.12. Atmospheric correction in extremely turbid waters

At the beginning of the BELCOLOUR-2 project, atmospheric correction algorithms (Moore et al. 1999; Ruddick et al. 2000; Stumpf et al. 2002) dealing with moderately turbid waters (e.g. up to 100 g/m3 TSM concentration) were becoming reasonably mature and reliable. However, these algorithms fail when confronted with extremely turbid waters, where there was a growing interest from users for optical remote sensing data, e.g. for the La Plata (Argentina/Uruguay), Gironde (France), Amazon (Brazil), Changjiang/Yangtze (China), etc.

In the BELCOLOUR-2 project (Dogliotti et al. 2011b) tested various atmospheric correction algorithms for extremely turbid, including the standard near-infrared (NIR) algorithm of (Stumpf et al. 2002; Bailey et al. 2010) and the SWIR-based algorithms of (Wang and Shi 2007) and (Wang et al. 2011), using MODIS_AQUA data for the La Plata estuary and river plume.

Results showed that **t**he standard NIR atmospheric correction completely failed for the river plume waters mainly due to sensor saturation and an incorrect estimation of the marine contribution in the NIR. The standard SWIR approach showed better results, but unphysical correlations between marine features and atmospheric products, such as aerosol reflectance, in the most turbid part of the estuary were clearly identified. The use of an iterative SWIR-based atmospheric correction approach that accounts for non-zero water reflectance in the SWIR bands performed best for retrieving accurate marine reflectance (Figure 17). The difference in the derived water reflectance between the two SWIR approaches showed a spectral dependence, being higher in the shorter wavelengths and lower in the NIR. A comparison between MODIS-derived turbidity values from the different atmospheric correction approaches and in situ data showed no significant differences mainly because the one-band turbidity algorithm applied uses the 859 nm band where differences between the approaches are lower.

The **implications** of this study are that optical remote sensing of extremely turbid waters is feasible at least for the MODIS-AQUA sensor, which has SWIR bands, and at least for parameters such as turbidity or TSM, which use red or near infrared bands. In combination with the study of section 3.8, this study helps to clarify the importance of SWIR bands for remote sensing of extremely turbid waters and hence improve the design plans of space agencies for the next generation of ocean colour sensors.

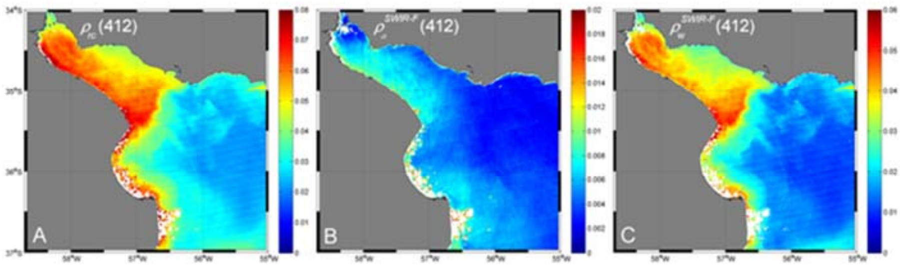


Figure 17 A) Rayleigh-corrected reflectance, B) aerosol and C) water reflectance at 412 nm retrieved from MODIS-Aqua image on Dec 20, 2010 using the SWIR-F approach and showing excellent decorrelation of aerosol and marine features. Reproduced from (Dogliotti et al. 2011b). © The author.

3.13.Diffuse attenuation coefficient

At the **beginning of the BELCOLOUR-2 project**, there was a clear user interest in optical remote sensing products relating to underwater light attenuation, horizontal visibilty (for divers and marine animals hunting prey visually) and euphotic depth and PAR attenuation coefficient (for primary production and eutrophication applications and related ecosystem model studies). Surprisingly the standard products for sensors such as SeaWiFS, MODIS and MERIS included, at most, a product for the diffuse attenuation coefficient at 490nm using a case 1 water algorithm not valid for most (case 2) coastal waters.

In BELCOLOUR-2, (Nechad et al. 2010) and (Nechad and Ruddick 2010) carried out a review of bio-optical models of the spectral diffuse attenuation coefficient for downwelling irradiance, Kd, and carried out numerical simulations to model KdZ1% the spectral diffuse attenuation of downwelling irradiance averaged over the euphotic depth Z1% (depth where the downwelling irradiance is 1% of its surface value).

Results established a relationship between KdZ1% at a single wavelength (590nm) and KPAR at ZPAR1% (where PAR is 1% of its value at the surface) which allows for a direct expression of KPARZPAR1% in terms of inherent optical properties, sun angle and cloudiness. The model provided estimates of KPAR within 25% (respectively 40%) relative errors respectively with a mean relative error less than 7% (respectively 9%) for sun zenith angles ranging from 0° to 50° (respectively higher than 50°). A similar method was used to derive a model for the diffuse attenuation of photosynthetically usable radiation, KPURZPUR1%, with similar performance.

This study has **implications** for ecosystem models (Lancelot et al. 2005; Lacroix et al. 2007), where the new formulation can be used in combination with both modelled CDOM fields (from salinity) and remotely sensed TSM fields to provide an estimate of PAR attenuation.

3.14. Estimation of CO2 partial pressure (pCO_2)

At the beginning of the BELCOLOUR-2 project, there was a strong user interest in using satellite-derived chlorophyll to provide information on the marine carbon cycle. Air-sea CO2 fluxes depend on air-water CO2 gradient controlled by physical and biogeochemical processes and the gas transfer velocity. A criticial parameter required for this flux calculation is the partial pressure of CO2 in seawater, pCO_2.

In BELCOLOUR-2, (Borges et al. 2010) carried out three cruises (April, July, September) per year for 2007-9 in the Southern North Sea. Measurements were made of pCO2, salinity and temperature as well as extra chemical parameters relevant for the marine carbon cycle. These datasets were used to derivemulti-parameter regression (MPR) algorithms for pCO_2 at 10°C as function of chlorophyll a and sea surface salinity (SSS). The MPR algorithms were used to estimate pCO_2 fields in Belgian waters for the cruise periods in 2007 based on remotely sensed chlorophyll a (from MERIS) and SSS estimated from the 3D hydrodynamical model of (Lacroix et al. 2004) and compared to the corresponding seaborne pCO_2 measurements.

The **implications** of this study are that it is possible to estimate pCO_2 at 10°C in Belgian waters by a combination of SSS estimated from a hydrodyanmical model and chlorophyll a estimated by satellite. This estimate of

pCO_2 at 10°C may then be further combined with information on sea surface temperature, obtained from models or measurements (e.g. from satellites), and on wind speed and atmospheric CO_2 to give an estimate of the air-sea flux of CO_2.

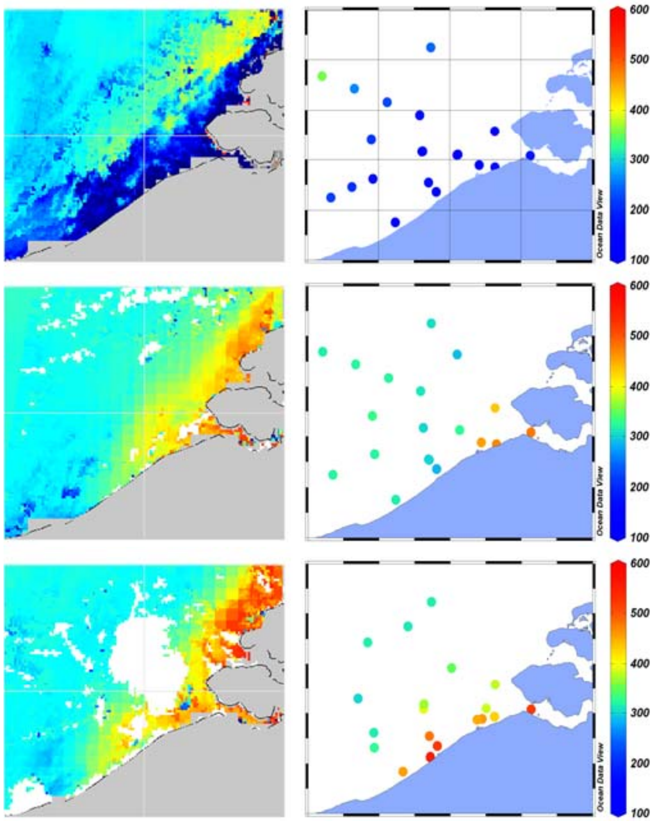


Figure 18 Comparison of derived (left panels) and measured (right panels) pCO2@10°C (ppm) in the Belgian coastal zone in Spring (top), summer (middle) and fall (bottom) 2007. White areas correspond to lack of CHL input because of clouds. Reproduced from (Borges et al. 2010). © ESA.

3.15. Ocean colour algorithms

While Sections 3.1-3.14 describe in detail studies lead by BELCOLOUR-2 scientists on aspects of ocean colour algorithms, the project has also contributed to a number of other studies via various external collaborations, including:

- A study by (Katlane et al. 2011) on mapping of TSM and turbidity in the Gulf of Gabes (Tunisia) using the methodology of (Nechad et al. 2010) and (Nechad et al. 2009).
- A study by (Vantrepotte et al. 2011) of suspended particulate matter in French Guiana coastal waters.
- A comparison by (Jamet et al. 2011) of atmospheric correction algorithms for turbid waters, including the algorithm of (Ruddick et al. 2000).
- A study on *Phaeocystis globosa* detection from hyperspectral and multispectral data, with similar objectives to and using the absorption spectra of (Astoreca et al. 2009) – see also Section 3.1.

4. Progress in exploitation and applications of ocean colour data

The research on marine optics theory (section 2) and ocean colour algorithms (section 3) has been motivated by interest in using ocean colour data for applications in coastal and inland waters. This motivation may be short-term, the usage of ocean colour data within the lifetime of the project itself, or long-term, via the development of algorithms and/or recommendations for the design of future ocean colour sensors, e.g. wavelengths required for detection of *Phaeocystsis* (Astoreca et al. 2009) or estimation of TSM in extremely turbid waters (Dogliotti et al. 2011a; Knaeps et al. 2012), advantages offered by geostationary sensors (Neukermans et al. 2009; Neukermans et al. 2012).

At the beginning of the BELCOLOUR-2 project there was already an established interest in exploiting ocean colour data for Belgian waters particularly from:

- ecosystem modellers (Lacroix et al. 2007) requiring information on light attenuation and chlorophyll concentration for forcing and validation of models used to study eutrophication and phytoplankton dynamics, and from
- sediment transport modellers (Fettweis et al. 2007) requiring information on suspended particulate matter for initialisation and validation of models used to study sediment transport for dredging/dumping and geomorphology applications.

In the BELCOLOUR-2 project, further applications of ocean colour data were made including:

- A review by (Rousseau et al. 2006) of phytoplankton dynamics in Belgian waters, which included the use of satellite-derived chlorophyll a to describe spatial and temporal variability of phytoplankton.
- A comparison by (Fettweis and Nechad 2011) of in situ and satellite-derived data for suspended particulate matter that included consideration of vertical profiles of SPM and the difference between near-bed data, often critical for sediment transport applications, and the near-surface data provided by satellites.
- A study by (Baeye et al. 2011 (submitted)) on the dynamics of suspended particulate matter in the Belgian-Dutch coastal zone, focussing particularly on variability of the coastal turbidity maximum according to winds and the spring-neap tidal cycle.
- A study by (Iluz et al. 2009) of short-term variability in primary production duing a wind-driven diatom bloom in the Gulf of Eilat (Aqaba).
- A study by (Borges et al. 2008) on net ecosystem production and carbon dioxide fluxes in the Scheldt estuarine plume, where satellite data was used to provide information on phytoplankton blooms and hence uptake of carbon.
- A study by (Larmuseau et al. 2009) on spatial variation in the rhodopsin gene of sand goby (*Pomotoschistus minutus*) in European waters, where a link was made between genetic variations, affecting colour vision of this visual predator, and the ambient light field as characterised by satellite estimates of the wavelength of maximally transmitted light.

Reviews were also made:

- by (Ruddick et al. 2008) of optical remote sensing applications in the North Sea, and,
- by (Ruddick et al. 2008) of phytoplankton-related applications of MERIS data in Belgian waters.
- By (Ruddick et al. 2008) on the validation of MERIS products in Belgian waters as a basis for exploitation of these products in applications.

5.The heritage from BELCOLOUR-2

The main heritage from the BELCOLOUR-2 project that will be carried forward into the future

consists of the body of publications (Annex A) that have been generation and the individual expertises that have been built up by the project scientists. BELCOLOUR-2 scientists have also contributed strongly to international workshops over the years – a list of conferences where BELCOLOUR-2 research has been presented is included in Annex B.
It is hoped that the BELCOLOUR publications will be used in the future, as the international community builds on existing knowledge and adds new ideas to advance our combined knowledge of marine optics and ocean colour remote sensing. In addition to these publications and the less tangible but very significant expertise of the project scientists a number of tools have been developed and made available to the scientific public to facilitate future research:

- An archive of daily maps of Total Suspended Matter and Chlorophyll a and (for MODIS) Sea Surface Temperature is made available from http://www.mumm.ac.be/BELCOLOUR/EN/Products/index.php. The extraction of digital data from this archive is currently also possible, but the future availability and expansion of this archive is subject to availability of funding.
- The Total Suspended Matter algorithm of (Nechad et al. 2010) has been supplied in tabular form at http://www.mumm.ac.be/BELCOLOUR/EN/Products/Software/index.php.
- The in situ reflectance, TSM and chlorophyll data collected by MUMM is being prepared with appropriate documentation as a publicly available dataset for testing of algorithms. A preliminary version is available via the Belgian Marine Data Centre.
- The 2007-2010 in situ dataset developed by ULB during the BELCOLOUR-2 project (including measurements on HPLC and spectrophotometric Chlorophyll-a, TSM, CDOM absorption, particulate, detrital and phytoplankton absorption, total in situ attenuation, in situ absorption and scattering) and published by Astoreca et al. (2009a, 2009b, 2012) is made available via the Belgian Marine Data Center (http://www.mumm.ac.be/datacentre). These data may be useful for algorithm validation.
- Water reflectance measurements from the Scheldt river: in situ dataset collected in 2010 from the Sint Anna pontoon in the Scheldt river. Water reflectance was measured using an ASD spectrometer registering data from 350 up to 2500 nm.

6.Conclusions and Future Perspectives

During the duration of the BELCOLOUR-2 project (Dec 2006-Jun 2012) there has been enormous progress in the field of ocean colour remote sensing. This progress has been driven by the availability of high quality, easily available satellite data, particularly from the MODIS-AQUA and MERIS sensors. Progress in algorithms for retrieval of new parameters has been considerable and the basic products of chlorophyll a and Total Suspended Matter concentration are now joined by a host of new products and applications, including phytoplankton species, turbidity, algae bloom timing, CO2 partial pressure, etc. Improvements in *in situ* instrumentation have allowed the study of microscale particulate optics. There have been improvements in many aspects of our understanding of absorption and scattering processes in the sea and how these processes are related to geophysical or ecosystem parameters and processes. These more fundamental studies build the basis for longer term potential applications of ocean colour remote sensing, revealing more and more information on marine processes. The BELCOLOUR-2 project has contributed to these developments by publishing research on a number of key issues and by presenting these at numerous workshops and conferences.

The BELCOLOUR-2 project is now finished and there is currently no possibility for funding a follow-on project of similar size and scope. The future for the BELCOLOUR-2 partners and scientists is thus fragmented and uncertain, although it is hoped that the expertise and the collaborations established during this project will survive in some way. Clearly the field of ocean colour remote sensing has a bright future internationally because of the planned launch of new operational missions such as VIIRS and Sentinel-3/OLCI as well as numerous more exploratory missions. It seems likely that the fast pace of progress seen in the field of ocean colour remote sensing over the last 10 years is likely to continue for the foreseeable future. Key challenges and ideas for the future include:

- the **improvement of the quality and the validation of basic products** such as marine reflectance and chlorophyll a in coastal waters. Atmospheric correction in situations with turbid water, absorbing aerosols, adjacency effects, and/or high air mass, etc. will continue to be important, as will quantification of chlorophyll a in the presence of other absorbing and/or scattering constituents.
- the design and exploitation of **geostationary ocean colour**
- the **exploitation of new spectral ranges such as the Short Wave Infrared** or a more intensive exploitation of the well-known visible/Near Infrared range in all its hyperspectral detail.
- the **use of new OLCI sensor** (onboard Sentinel-3) data for detection of phytoplankton groups in combination with Flow-Cam. Since this new sensor lacks of the appropriate wavelength for *Phaeocystis globosa* detection (Astoreca et al. 2009a) other wavelengths should be tested in order to detect this group in the Southern North Sea.
- the improvement of the **fundamental optics of particles** at the microscale and how this impacts remote sensing algorithms, e.g. as regards mass-specific optical properties.
- improvement of the **understanding of photosynthesis** and how the light field affects phytoplankton dynamics
- the **use of spectral fluorescence** for the identification of phytoplankton groups. Results on spectral fluorescence of phytoplankton are encouraging since identification of some phytoplankton groups is possible, e.g. cyanobacteria in the Baltic Sea. Current measurements are being performed in cultures from the Southern North Sea and results will give insight into the possibility to detect phytoplankton as *Phaeocystis globosa* in this area. If the appropriate wavelength(s) are present in the OLCI sensor, this could open a new era for remotely sense *Phaeocystis* in coastal waters.
- **understanding how light affect animal life** in the sea via processes such as visual predation, bioluminescence, communication, navigation, etc.
- the **retrieval of new information on the marine ecosystem** by creative exploitation of the remotely sensed radiance signal in terms of its radiometric, spectral, spatial, temporal, directional and/or polarimetric variability.
- the **intensification and operationalisation of applications** such as coastal water monitoring and the extension to relatively new contexts such as inland waters.
- **operationalisation for the OLCI sensor of the new primary production algorithm** designed for use in the Southern North Sea (Rousseau et al. in preparation). The demonstrated sensitivity of the algorithm performance to the modelled value of the maximum photosynthetic capacity requires additional field measurements of this phytoplankton parameter. This could be performed by using Pulse Amplitude Modulation (PAM) fluorometry, for which a measurement protocol has been developed in the Southern North Sea during the BELCOLOUR-2 project.

- **the retrieval of phytoplankton functional types using APEX** hyperspectral imagery.
- **the regionalisation of aerosol optical properties**. In the APEX atmospheric correction, standard aerosol properties are used which may deviate from the actual aerosol properties. A regionalisation of aerosol optical properties (as phase function or asymmetry factor, single scattering albedo) on basis of a clustering analysis of AERONET data will reduce the uncertainty of the atmospheric correction.
- **error propagation in image (pre)processing up to level 3 and influence on water quality products**. The scope here is to quantify the effect of uncertain input parameters on the processed Level 2 (i.e. reflectance) product and propagate this to two Level 3 water products such as Suspended Particulate Matter (SPM) concentration maps and Chl-a concentration maps.
- **exploration of the potential use of Sentinel 2 for inland water quality monitoring**. With its relatively high spatial resolution coupled with a revisit time of 5 days, Sentinel-2 offers the opportunity to monitor small inland water bodies to support the European Water Framework Directive which forms the legislative framework for the water management undertaken by the EU Member States.

The approach to tackling most of these challenges will require a multidisciplinary team of dedicated researchers with strong international contacts, as was built up during the lifetime of the BELCOLOUR-2 project.

7.Acknowledgements

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The Steering Committee members (Emmanuel Boss, Roland Doerffer, Claudia Giardino, Miguel Berteloot, André Cattrijsse, Guido Dumon, Jean-Paul Huot, Steef Peters, Kris Vannieuwenhove) are thanked for their constructive criticism and for their many suggestions. The annual Steering Committee meetings were important moments where the project came under intense scrutiny and friendly criticism and received valuable encouragement to proceed with this research.

The North Sea fieldwork was carried out with the expert assistance of the captains, crews and support staff of the Research Vessels *Belgica* and *Zeeleeuw*.

Satellite data for the various studies was received from the European Space Agency (MERIS), NASA (MODIS), EUMETSAT and KMI/IRM (SEVIRI).

Assistance was provided to the project by MUMM's computer team, CAMME, and webmaster, Fabrice Ovidio.

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Annex A. List of BELCOLOUR-2 publications

The following publications were produced by the BELCOLOUR-2 project, either alone or in collaboration with other projects/institutions. BELCOLOUR-2 scientists are denoted in **bold**.

Peer-reviewed (published/accepted)

Astoreca, R., D. Doxaran, K. Ruddick, V. Rousseau and C. Lancelot (2012). "Influence of suspended particle concentration, composition and size on the variability of inherent optical properties of the Southern North Sea." Continental Shelf Research, . Vol. 35, p. 117-128, http://dx.doi.org/10.1016/j.csr.2012.01.007.

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Sirjacobs, D., A. Alvera-Azcárate, A. Barth, **Y. Park, B. Nechad, K. Ruddick** and J. M. Beckers (2008). Cloud filing of total suspended matter, chlorophyll and sea surface temperature remote sensing products by the Data Interpolation with Empirical Orthogonal Functions methodology. Application to the BELCOLOUR-1 database. 2nd MERIS (A)ASTR workshop, Frascati, Rome, Italy.

Annex B List of BELCOLOUR conference contributions

BELCOLOUR research was presented at the following international conferences:

- 44th Liège Colloquium on Ocean Dynamics “Remote Sensing of Ocean Colour, Salinity and Temperature”, held at the University of Liège from 7 to 11 May 2012 (4 oral presentations, 2 posters).
- Griet Neukermans’ PhD thesis at the Université du Littoral Côte d’Opal, 18th April 2012.
- EARSeL 7th SIG-Imaging Spectroscopy workshop, U.K. (11-13th April 2011) (1 oral presentation)
- Coastcolour user consultation meeting 16-17 November 2010, Frascati
- Particles in Europe workshop in Villefranche, France (15-17 Nov. 2010) (2 presentations)
- International Conference on Airborne Research for the Environment (ICARE)**,** Toulouse, October 25th-31st 2010
- EurOCEAN 2010 Conference, 12-13 October 2010, Oostende, Belgium
- SPIE Asia-Pacific Remote Sensing, 11-14 October 2010, Inchoen, Korea
- Ocean Optics XX conference in Anchorage, USA (27^{th} Sept-1^{st} Oct 2010) (4 presentations)
- ESA Living Planet, , 28 June-2 July, 2010, Bergen (1 oral presentation)
- Oceans from Space conference in Venice, Italy (26-30^{th} April 2010) (1 poster presentation).
- 42^{nd} Liège Colloquium on Ocean Dynamics “Multiparametric observation and analysis of the Sea”, held at the University of Liège from 26-30 April 2010 (1 presentation).
- MERIS Validation Team meeting, Lauenburg, 29-30 March 2010
- MERIS Validation Team meeting held in Oslo 20-21^{st} October 2009 (1 oral presentation).
- GOCI PI meeting and the IOCCG working group meeting on geostationary sensors in Cheju-DO, Korea (29^{th} October – 1^{st} November 2009).
- SPIE conference "Remote Sensing of the Ocean, Sea Ice, and Large Water Regions 2009" held in Berlin 31^{st} August-3^{rd} September 2009. (1 oral presentation)
- SPIE conference on "Ocean Remote Sensing: Methods and Applications" held in San Diego, August 2009 (1 oral presentation)
- Remote sensing and water optics specifically for Baltic Sea conditions, 20-21 August 2009 Tallinn, Estonia (1 oral presentation)
- 4th EARSeL Workshop on Remote Sensing of the Coastal Zone Details Programme. Chania, Crete, Greece, 17-20^{th} June 2009
- GEO Inland and Coastal Water Quality Algorithm workshop held in Washington DC, on 19-21^{st} May 2009
- 33rd International Symposium on Remote Sensing of Environment, May 4-8, 2009, Stressa, Lago Maggiore, Italy (1 poster presentation)
- 41st International Liege Colloquium on Ocean Dynamics, held in Liège, 4-8 May 2009 (1 poster presentation)
- EUFAR-HYQUAPRO expert working group on in-water algorithms and atmospheric corrections, held in Wageningen on 19 April 2009.
- NASA Ocean Colour Research Team meeting held in New York, April 2009 (1 poster presentation)
- 6th EARSel SIG IS Workshop, held in Tel Aviv 16-19 March 2009.

- MERIS Validation Team meeting held in Faro, 3-4th March 2009 (1 oral presentation)
- EUFAR FP7 JRA2 "HYQUAPRO: Quality layers for airborne hyperspectral imagery and data products" Kick Off meeting, Mol, 21 and 22th November 2008.
- RESORT project final meeting, Mol (20th October 2008)
- "Particles in Europe" conference held in Bologna, 13-14th October 2008 (1 oral presentation)
- OceanOptics2008 conference in Barga, Italy on 6-10th October 2008 (1 oral, 6 poster presentations)
- MERIS Users conference organised by the European Space Agency, 22-26th September 2008 (2 oral presentations, 1 poster presentation).
- BENCORE conference, Leuven (30th May 2008): 1 oral presentation, 1 poster presentation
- 7th International Conference on Environmental Problems in Coastal Regions VII (COASTAL ENVIRONMENT 2008), held in The New Forest (UK) on 19-21th May 2008
- GAP international workshop on Primary Production held in Eilat, Israel from March 30-April 8 2008 (1 poster)
- VLIZ *Jongerencontactdag* on 29th February 2008 (2 posters).
- BELSPO STEREO conference in Namur (12th February 2008): 1 oral presentation and 1 poster presentation
- EGU General Assembly 2008 (Vienna, Austria): 2 posters
- EARSEL symposium on Imaging Spectroscopy held in Brugge on 23-25th April 2007: one poster presentation.
- VLIZ jongerencontactdag held in Brugge on 2nd March 2007: one poster
- EARSEL symposium on Remote Sensing of the coastal zone, held in Bolzano on 7-9th June 2007: one oral presentation
- ENVISAT symposium in Montreux on 23-27th April: one oral presentation
- 6de Waterforum: Informatie voor Watersysteemkennis', held in Antwerp on 4th October 2007: one flyer.
- 3Rd CARBOOCEAN annual meeting (Bremen, December 3-7 2007): one poster

Annex C Administrative Informative

This information is confidential and for BELSPO information only.

8.1. Steering Committee composition

The BELCOLOUR-2 steering committee was composed of
Emmanuel Boss, University of Maine, USA
Roland Doerffer, HZG, Germany
Claudia Giardino, CNR, Italy
Miguel Berteloot, Afdeling Kust
André Cattrijsse, VLIZ
Guido Dumon, Afdeling Kust
Jean-Paul Huot, European Space Agency
Steef Peters, Water Insight, Netherlands
Kris Vannieuwenhove, ILVO

8.2.Web site

The BELCOLOUR-2 project web site can be found at:
http://www.mumm.ac.be/BELCOLOUR

8.3. Partner information – MUMM

8.3.1. Personnel employed

Bouchra Nechad, Griet Neukermans (until 2011, now at Scripps Institute of Oceanography, USA) and Youngje Park (until 2008, now at the Korean Ocean Satellite Centre, South Korea) and Barbara Van Mol (until 2007, now at DEME) were employed by the BELCOLOUR-2 project.

8.3.2. Obstacles

During the course of the project, no extraordinary obstacles were encountered. The main difficulty for MUMM is the lack of a STEREO framework for continuation of activities and funding of research staff after the end of the project. The expertise built up during the project and the collaborations established with BELCOLOUR partners and with international researchers may be lost if there is no funding for staff. A more permanent framework for exploitation activities, for example based on the improvement and expansion of the BELCOLOUR satellite data archive would better ensure uptake of the research into long-term applications.

8.3.3. Relevance of project results for partner

The BELCOLOUR-2 project has formed the basic core funding of the remote sensing research activities at MUMM, enabling the team to develop internationally to a strong position in the ocean colour coastal water community. The products generated have also been of interest to colleagues at MUMM focussing, for example, on sediment transport and ecosystem modelling.

8.4. Partner information – ULB/ESA

8.4.1. Personnel employed

Rosa Astoreca (currently seeking employment) was employed by the BELCOLOUR-2 project.

8.4.2. Obstacles

The main obstacle for ULB/ESA was the limited budget for staff.

8.4.3. Relevance of project results for partner

The BELCOLOUR-2 project was valuable to ULB/ESA particularly because of the synergy between experimental eco-physiological studies, ocean color products and modelling.

8.5.Partner information – VITO

8.5.1. Personnel employed

Sindy Sterckx, Els Knaeps, Carolien Tote and Dries Raymaekers (currently all still at VITO) were employed by the BELCOLOUR-2.

8.5.2. Obstacles

The main obstacle for VITO was the limited budget and time to finalize publications.

8.5.3. Relevance of project results for partner

An adjacency correction method was developed which can be applied to both airborne and satellite date. As a data provider of airborne data this correction is important to improve the quality of the collected images.

Evidence was found of non zero water reflectance in the SWIR for the Scheldt river. As VITO is focusing on inland and coastal waters where sediment concentrations reach very high values, these new findings could lead to an improvement of the water quality estimates in these waters. Moreover, VITO's airborne instrument, APEX, has wavelengths in the SWIR thereby providing a new research interest.

8.6.Partner information – ULg

8.6.1. Personnel employed

Willy Champenois (1/2 time) and Jérôme Harlay (full time). They were both involved in data collection during the Becloulour cruises, chemical analysis from those cruises and data processing.

8.6.2.Obstacles

The main obstacle for ULg was the limited budget. The other obstacle is the lack of calls for project that would allow the continuation of the work we started, and also that would allow extend a joint remote-sensing and marine biogeochemistry analysis.

8.6.3.Relevance of project results for partner

BELCOLOUR-II was the first project involving remote sensing algorithm development that the Chemical Oceanography Unit was involved. This expanded the expertise of the Unit. Also, during the Belcolour-II cruises we collected for the first time spatially resolved data on methane (CH4) and nitrous oxide (N2O) off the Belgian coastal zone. Although not explicitly a Belcolour-II task, these new and exciting data should lead to a publication and the first description of these variables off the Belgian coastal zone.

8.7.Partner information – LOV

8.7.1. Personnel employed

David Doxaran (still employed at LOV) worked at LOV on the BELCOLOUR-2 project. Bernard Gentili and Edouard Leymarie have also contributed to the project through numerical simulations of marine optics.

8.7.2. Obstacles

During the course of the project, no extraordinary obstacles were encountered. The main difficulty concerned the measurement in the field of light backscattering measurement: the use of the Wetlabs ECO-BB3 sensor purchased as part of the project proved to be adapted to sample the moderately turbid waters but not to the highly turbid waters of the southern North Sea. This was a choice made in terms of sensor specifications in order to have an optimal sensitivity in 90% of the waters sampled.

8.7.3. Relevance of project results for partner

The BELCOLOUR-II project was a great opportunity for LOV to sample (in the field and laboratory) and model the inherent optical properties of complex coastal waters (the southern orth Sea). The collaboration with the different partners (mainly MUMM and Ulg, both involved in marine optics research activities) has been a great experience which allowed developing an unique optical and biogeochemical database and making significant progress in the understanding of coastal waters optical properties (e.g., influence of particle absorption and size distribution on light scattering and attenuation).

8.8.Partner information – CSIRO

8.8.1. Personnel employed

The CSIRO staff involved in the international scientific activities of Belcolour were: Dr. Thomas Schroeder, Dr Vittorio Brando, Dr YoungJe Park (from 2008-2010) and Dr. Arnold Dekker

8.8.2.Obstacles

In the initial phase too much attention had to be paid by K. Ruddick and A. Dekker to reconcile compulsory Dutch/French contracts with CSIRO's compulsory English contracts; mismatches in financial years also contributed to administrative burden. The distance was an issue for easy exchange of staff and instruments

8.8.3.Relevance of project results for partner

There are only a few research and applications groups in the world that are tackling the scientific issues of developing management relevant applications of earth observation for optically complex waters. BelColour was able to involve many of these experts and therefore the interaction between CSIRO and BelColour has been highly appreciated. Visits were paid to MUMM and other BelColour partners by Young Je Park, Thomas Schroeder, Vittorio Brando and Arnold Dekker, and wherever international conferences brought BelColour scientists and the international partners together more lively interactions took place. By sharing methods and data it was possible for CSIRO to compare and validate atmospheric correction algorithms over a representative globally valid set of optically complex waters. The BelColour work on protocols and on inherent and mass specific inherent optical properties, PCO2 etc., is at the highest international level and of high relevance to CSIRO's aim to develop similar approaches in Australia. Especially important is exchange of ideas and data as we are with so few groups in the world with a longer term capability and capacity in this area. It would be very detrimental to the scientific and applications world if there was no continuity in on-going investment in this state of the art scientific team in Belgium. CSIRO has taken specific approaches to specific inherent optical property adaptively parameterised algorithms as well as radiative transfer based artificial neural networks for atmospheric correction: CSIRO needs to test these innovative methods by interacting with other expert teams such as BelColour was able to create.