Inter-comparison of atmospheric correction algorithms over optically-complex waters

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I. Scientific and programmatic background and rationale

The use of satellites to monitor the color of the ocean requires effective removal of the contribution of the atmosphere (due to absorption by gasses and aerosols, and scattering by air molecules and aerosols) from the total signal measured by the remote sensor at the top of the atmosphere (TOA): the so called "atmospheric correction" (AC) process. The methods for removing the contribution of the atmosphere to the total measured signal exploit the high absorption by seawater in the red and near-infrared (NIR) spectral regions (λ>700 nm). In open seawater, i.e. where generally chlorophyll-a concentration and related pigments and co-varying materials (like detritus) determine the optical properties of the ocean, seawater can be considered to absorb all light in the NIR so that the signal observed by the satellite sensor in this spectral domain is assumed to be entirely due to the atmospheric path radiance (La) and the radiance reflected at sea surface. However, this is not always the case when considering turbid waters (generally coastal optically complex waters) dominated by CDOM and/or suspended particulate matter. In these waters phytoplankton pigment and detritus, as well as inorganic suspended sediment associated with river discharge or resuspension, contribute to NIR backscatter. The resulting NIR water-leaving radiances (Lw) introduce two sources of error into the removal of the path radiance. Firstly, the total aerosol reflectance is overestimated as particulate matter the seawater partly contributes to the total NIR radiance.. Secondly, the absorption and scattering properties of seawater change due to these additional substances resulting in the selection of an inappropriate atmospheric model, which then is causing errors in the extrapolation of La to shorter wavelengths. As a result, La is overestimated at all bands with increasing values at shorter wavelengths, even possibly leading to negative water-leaving radiances in the blue bands in coastal waters (Siegel et al., 2000). This results in severe errors, if not complete failure, for algorithms that rely on de-coupling atmospheric and oceanic radiance signals to retrieve concentrations of water constituents or their inherent optical properties.

To overcome this problem, several methods to extend the AC algorithm have been developed in recent years that account for non-negligible water-leaving radiance contributions to the total TOA signal (Bailey et al., 2010; Brajard et al., 2012; Doerffer and Schiller, 2008; Dogliotti et al., 2011; Gould et al., 1998; Hu et al., 2000; Kuchinke et al., 2009; Land and Haigh, 1996; Lavender et al., 2005; Li et al., 2008; Moore and Lavender, 2011; Oo et al., 2008; Ruddick et al., 2000; Schroeder et al., 2007; Shanmugam and Ahn, 2007; Shanmugam, 2012; Stumpf et al., 2003; Wang et al., 2005, 2009, 2012). In the rest of the proposal, the term atmospheric correction (AC) will mean the methods that extend the AC algorithm to optically-complex waters.

However, only a few studies have been made to date that evaluate those AC in optically complex coastal waters from in-situ measurements (Banzon et al., 2009, Jamet et al., 2011, Goyens et al., 2012 for instance). More recently, a comparison of the standard (operational) AC algorithms for the SeaWiFS/MODIS, MERIS, OCTS/GLI and POLDER sensors above clear and turbid ocean waters was completed by a working group (WG) of the International Ocean Color Coordinating Group (IOCCG, 2010) chaired by Menghua Wang. This WG focused mainly on open ocean waters and included only two simulated cases of optically-complex waters; (1) a typical sediment-dominated and (2) a yellow substance dominated case. For sediment-dominated water, the results showed that, for a weak aerosol optical thickness (0.1), errors in the estimated normalized water-leaving radiance (nLw) at 443, 490 and 555 nm varied from 7-25%, 5-15%, and 4-10%, respectively. For the yellow substance-dominated waters, the comparison showed that it was very difficult to accurately estimate the normalized water-leaving radiance from satellite sensor measurements, especially at shorter wavelengths. Results showed significantly large errors in the estimated nLw(443) from all four algorithms and smaller errors at 490 nm and 555 nm.. Moreover, the algorithms presented for the SeaWiFS and MODIS sensors are not the currently standard ones since 2007 and the algorithm for MERIS sensor is not the algorithm applied for optically-complex waters. One chapter of the 2010 IOCCG report was dedicated to the presentation of alternative, non-operational AC algorithms, however without evaluation of their performance. Therefore, it is necessary to complete and to update the 2010 report with a more complete comparison of atmospheric correction algorithms over optically-complex waters.

Lately, an inter-comparison exercise was done in the framework of the Climate Change Initiative for MERIS sensor, focusing also only on open waters.

An inter-comparison and evaluation of existing AC algorithms over optically-complex waters is required to understand retrievals differences since the algorithms are often based on different physical assumptions. The challenge for this WG will be to understand the advantages and limitations of each algorithm and their performance under certain atmospheric and oceanic conditions, for example different the water types. The proposed WG will only focus on AC algorithms that deal with optically-complex waters, i.e. a non-zero NIR water-leaving radiances. There is a high demand for AC guidelines by the international ocean color community as more and more remote sensing studies focus on

coastal zones. The outputs of the WG are therefore timely and will provide guidelines on the use of atmospheric correction algorithms over optically-complex waters and ultimately recommendations for improving and selecting the optimal AC for a given water type.
To evaluate AC performance a round-robin inter-comparison will be performed based on three datasets; (1) *in-situ* measurements, (2) radiative transfer simulations and (3) satellite observations. The selected AC will be evaluated through match-ups analysis and sensitivity studies. The first step, before evaluating the atmospheric correction algorithms, will be to select different algorithms based on their hypothesis. The goal of this WG is not to evaluate and inter-compare all the published atmospheric correction algorithms. The comparison will be performed only for selected algorithm classes based on different hypotheses such as aerosol model selection, bio-optical models and/or inversion/mathematical methods. For example, one can consider that the algorithms of Hu et al. (2000) and Ruddick et al. (2000) are similar as they both consider a fixed atmosphere (i.e. same aerosol model over the region of interest).

These three datasets will have different purposes. Once the AC algorithms will be selected, the first evaluation will be a classic match-ups exercise. For this purpose, in-situ datasets will be gathered from existing databases such as NOMAD, MERMAID, AERONET-OC or COASTCOLOR. This work will be done in close collaboration with the IOCCG WG on Intercomparison of Retrieval Algorithms for Coastal Waters led by Kevin Ruddick as this WG is already gathering in-situ datasets for evaluating in-water retrieval algorithms. The in-situ dataset will also be used to study the algorithm performance depending of the water types. Classification of water types (such as Vantrepotte et al., 2012) will be used to differentiate the coastal ocean waters upon their material contents and concentrations. As these water types depend on the water composition, it is informative to study the error retrievals of the AC algorithms. These errors may provide information on the bio-optical algorithms used for each AC but also on the inversion technique when the bio-optical algorithm really differs from the sea-truth. One specific study will be to compare the retrieved nLw in the near-infrared wavelengths (between 700 and 900 nm). As the goal of one class of atmospheric correction algorithms is to remove the atmosphere and to account for a non-zero nLw(NIR), it is interesting to evaluate their abilities to estimate nLw in the near-infrared.

As in-situ datasets are limited and rarely represent the entire natural variability of the oceanic and atmospheric constituents, radiative transfer simulations will be performed for a wide range of parameters (very weakly to absorbing aerosols, oligotrophic to extremely turbid waters). The goal is to compile a representative simulated datasets of situations that can occur over optically-complex waters. This simulated dataset will be used for sensitivity studies to evaluate aerosol model selection and the retrieval of water constituent concentrations such as the concentration of chlorophyll-a, CDOM and SPM. As all the parameters can be controlled when using simulated datasets, additional sensitivity analysis will be performed for a fixed atmosphere (i.e. fixed aerosols models and concentrations) or fixed water constituents. This exercise will help to verify the validity of the hypotheses of each selected AC and their limits when considering extremely turbid waters or very absorbing aerosols for instance.

At last, the selected algorithms will be applied to satellite observations (SeaWiFS, MODIS-AQUA, VIIRS, MERIS) over selected regions (Eastern English Channel/North Sea, French Guiana, Vietnam among others). The selected areas will be chosen, among other criteria, for their level of oceanic and atmospheric turbidity, including weakly or very absorbing aerosols. The spatial distribution of estimated aerosol parameters will be compared to the spatial distribution of nLw identify correlations that indicate AC failure Moreover, transects from the coast to the open ocean will be extracted to study the behaviour of the AC algorithms as a function of the turbidity. This allows studying the capability of each AC to perform over a wide range of turbidity levels and to observe any spatial artifacts. Moreover, the satellite dataset will be used to generate time series over the selected areas to compare the temporal variability produced by the selected AC algorithms..

This WG will mainly focus on the inter-comparison of atmospheric correction algorithms over optically-complex waters but also briefly touch on other issues, such as adjacency effects and absorbing aerosols. One dedicated chapter will provide a review of existing adjacency correction algorithms and issues related to absorbing aerosols. Dealing with absorbing aerosols over optically-complex may be the most challenging issue in the field of atmospheric correction.

Further, this WG is timely because of potential synergies with the recently established WG on Intercomparison of Retrieval Algorithms for Coastal Waters. The proposed WG will benefit from the datasets developed and gathered by this WG and this latter will benefit from the error analysis of the AC round-robin.. Moreover, this work will benefit to the IOCCG WG on Uncertainties in Ocean Colour Remote Sensing for the same reason. One distinct difference of the proposed WG is to provide guidelines/recommendations for using and improving AC over optically-complex waters.

II . Terms of reference

1. Evaluation of state-of-the art of AC algorithms dealing with Lw(NIR) >0 (Coupled ocean-atmosphere model, NIR adjustment, SWIR) with the range of validity/limitations of each algorithm published in the literature
2. Compilation of three datasets needed for the inter-comparison by harvesting already existing databases and satellite archives and conducting RT simulations:
    - Simulated with a wide range of parameters (this work will be done with close link to the new IOCCG WG on bio-optical algorithms comparison in coastal waters and the databases developed from IOCCG report #10)
    - In-situ: several datasets already exist that could benefit to this WG. Participants of this WG have their own databases. Other datasets

could be MERMAID, AERONET-OC, COASTCOLOR for validation in the visible. These require prior consent of the PIs. One goal will be to gather datasets with measurements for wavelengths > 700 nm.

- Satellite imagery: SeaWiFS, MODIS-Aqua, MERIS, VIIRS for quality control and regions of success and failures (range of geometry). Only MODIS-Aqua will be applicable for SWIR studies (potentiality OLCI depending on launch date).

3. Documentation of the protocols used to inter-compare the different AC algorithms (Match-up exercise, transects extraction from very turbid to clear waters, time series, sensitivity studies, format of the datasets, all algorithms in one software, ...). The main parameter taken into account is the water-leaving radiance.
4. Sensitivity studies using simulated and in-situ datasets providing the limitations of each algorithm.
5. Discussion about uncertainty budgets.
6. The activity of the WG, i.e. the inter-comparison results and evaluation will be gathered in a report to provide recommendations on range of validity and limitation of each algorithm. The report will summarize the results of items 4-5. One chapter of the report will present a review the other issues related to AC such as cloud and shallow water masking, absorbing aerosols and adjacency effects..

III. Proposed membership (list contains people that have already mentioned their active participation to the WG)

- Sean Bailey, NASA, USA
- Julien Brajard, LOCEAN, France
- Cédric Jamet (Chairman), LOG ULCO/CNRS, France
- Xianqiang He, SIO, China
- Kevin Ruddick, MUMM, Belgium
- Palanisamy Shanmugam, ITT, India
- Thomas Schroeder, CSIRO, Australia
- Knut Stamnes, Stevens Institute of Technology, USA
- Sindy Sterckx, VITO, Belgium
- Menghua Wang, NOAA, USA

IV. Draft time line

- Months 0-6:
  - Bibliography of the different AC algorithms
  - Gathering of the simulated, in-situ, satellite datasets
  - Implementation of algorithms in SeaDAS for easy comparison (if necessary)

- Months 6-18:
  - Validation and evaluation

    - Sensitivity study

- Months 18-24:
    - Harmonization of the results
    - Report