Inland and coastal water remote sensing: current status and future directions in the correction of adjacency effects

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Introduction

The Global Climate Observation System (GCOS) includes Ocean Color (OC) and Lakes among the Essential Climate Variables (ECVs) to support the work of the United Nations Framework Convention of Climate Change (UNFCCC). Their actual application to climate monitoring foresees goal measurement uncertainties lower than 5% and 10% for OC and Lakes radiometric products, respectively. These requirements are particularly challenging in coastal and inland waters, whose optical complexity resides on the simultaneous presence of non-covarying in-water optically active components (i.e., pigments, colored dissolved organic matter and suspended sediments), high turbidity and potential contributions from bottom and nearby land. Nonetheless, the economic and environmental importance of lakes and coastal zones is widely acknowledged, while their habitats are extremely sensitive to the impacts of climate variability and change.

In general, standard algorithms for the processing of satellite data assume an infinite water surface, thus neglecting the presence of nearby land when inland and coastal waters are imaged. As a consequence, the radiance reflected by the land and then propagated by the atmosphere in the field-of-view of a satellite sensor observing a water target represents a perturbation leading to uncertainties in satellite products. This phenomenon, called adjacency effects (AE), always occurs in the presence of a scattering medium overlaying a non-homogeneous surface, while its impact varies over space and time. The workshop aims at gathering the scientific community to review state-of-the-art knowledge on the quantification of AE in satellite imagery from inland and coastal water regions, to identify potential gaps/opportunities for its operational correction, and to individuate areas of collaboration.

The overarching goal is to provide recommendations to the space agencies, the community, and the IOCCG Committee to enhance the quality of satellite water products in complex but critical inland and near shore coastal waters.

Key Questions

1. Which parameters should be utilized to quantify AE in satellite data from coastal and inland waters? This will aim at establishing a consensus in the parameters utilized to quantify AE in satellite data from inland and coastal waters.

2. Which is the state-of-the-art knowledge on the impact of AE in satellite data from coastal and inland waters? This will aim to overview available tools for the

quantification of AE, and to identify key AE dependencies, feasible approximations, as well as aspects that still need to be addressed.

3. Which are the current available algorithms for the operational correction of AE in satellite data from coastal and inland waters? Which existing gaps, development directions and areas of collaborations can be envisaged? This will aim at inventorying current potential algorithms for the operational correction of AE in satellite radiometric data from coastal and inland waters. It will additionally aim to identify gaps and research needs, as well as areas of collaborations (with specific focus on AE algorithm intercomparison and validation with in-situ data).

Session Summary

The session featured several presentations from academia and industry (consultancy companies) covering theoretical foundations, algorithm development, operational implementations, and validation of AE correction methods.

Barbara Bulgarelli (JRC) gave a general introduction, setting the scene for discussion and highlighting some key elements, such as the strong dependence of biases induced by AE in satellite primary products on the applied atmospheric correction scheme. Examples were given of algorithms retrieving the atmospheric properties from the NIR that might induce consistent biases in the derived water-leaving radiance at blue/green bands as a consequence of the propagation in the visible bands of AE at the NIR. AE have multifold dependencies often requiring the implementation of approximations to simplify AE modeling and correction. Based on results from NAUSICAA Monte Carlo simulations, examples were given highlighting, among others, the need to account for the sensor viewing angle, as well as for the water surface reflectance anisotropy.

Carsten Brockmann (Brockmann Consult) addressed the practical question of when AE correction is necessary from an operational service perspective. While lake-center monitoring for applications in support of, e.g., the Water Framework Directive may tolerate rejection of AE-contaminated pixels, narrow water bodies and near-shore pixels require explicit correction. The presentation underlined the need to quantify AE and related uncertainties before correction, to validate AE correction methods, and to better understand aerosol dependences.

François Steinmetz (HYGEOS) presented SMART-G Monte Carlo radiative transfer simulations to assess AE impacts on atmospheric correction algorithms. The work confirmed significant variability in algorithm sensitivity: standard algorithms showed strong contamination from adjacent vegetation affecting aerosol retrieval in red/NIR bands and propagating uncertainties to blue/green bands, while the Polymer algorithm demonstrated implicit mitigation of ice and snow effects due to their spectrally flat albedo. Integration of T-Mart AE correction with Polymer showed improvements in the presence of nearby vegetation.

Four AE correction approaches were presented. Thomas Heege (EOMAP) described the MIP (Modular Inversion and Processing) AE correction processor, a physics-based sensor-agnostic approach operational since 2014 across multiple sensors for water quality and bathymetry applications. The method uses iterative aerosol retrieval and employs analytical point spread functions accounting for arbitrary coastline geometries. Simon Bélanger (University of Quebec) introduced the Genetic Algorithm for Atmospheric Correction (GAAC), which models the gas-Rayleigh-corrected signal through four contributions (remote sensing reflectance via 5-component bio-optical model, aerosol reflectance from OPAC models, sun glint, and adjacency reflectance). GA optimization showed good performance on RAdCor validation data, though computational costs remain high (approximately 10 minutes for one single pixel). Yulun Wu (University of Ottawa) presented the Topography-adjusted Monte-Carlo Adjacency-effect Radiative Transfer (T-Mart) code, an open-source tool for the modeling and correction of AE that demonstrated consistent bias reduction in Sentinel-2 and Landsat-8 near-shore matchups when integrated to ACOLITE, POLYMER and l2gen atmospheric correction schemes. Alexandre Castagna (University of Ghent), in collaboration with Quinten Vanhellemont (Royal Belgian Institute of Natural Sciences), presented the RAdCor processor, which accounts for AE in the ACOLITE atmospheric correction suite. Together with RAdCor, ACOLITE now includes the TSDSF module that estimates aerosol properties from the imagery even under AE. ACOLITE is free and open source, and several sensors are supported for AE correction.

Alexandre Castagna and Quinten Vanhellemont highlighted the relevance of small and narrow aquatic systems, representing the vast majority of inland water systems (>99%) still being the most affected by AE due to reduced dimensions. They provided a validation and intercomparison framework with other codes for Landsat-8/OLI and Sentinel-2/MSI over Belgian lakes and for a global dataset from the RAdCor early adopters group. They finally illustrated examples of AE mitigation in codes that do not explicitly account for AE and explored the still large uncertainties in the NIR region, despite the large improvement provided by AE correction codes.

The gathered community (more than 100 attendees) agreed on the importance of raising awareness about the need to correct for AE in coastal and inland waters. Despite good progress, further algorithm development and validation is considered fundamental for future operational applications.

Key gaps and research needs identified by presentations and open-discussion included: the importance of performing intercomparison exercises utilizing in-situ reference data and/or synthetic (simulated) datasets; the limited availability of high-quality validation datasets in adjacency-impacted areas (small and narrow inland waters, near-shore coastal areas in marine and large lakes); underdeveloped uncertainty characterization for AE correction schemes; unaddressed questions regarding incorporation of digital elevation models and polarization (especially in the presence of sunglint); differentiation between AE and imagery artifacts (ghosting, stray light); need to better characterize the aerosol optical properties and to account for spatial and vertical aerosol heterogeneity; need to investigate impacts of air pressure uncertainties in Rayleigh-dominated spectral regions; inaccuracies induced by assuming an isotropic surface reflectance; uncertainties induced by broken clouds and swath edges; usefulness of including flags to warn users on potential inaccuracies induced by uncorrected AE.

Review of Existing IOCS Recommendations

Adjacency effects fall within the topic of atmospheric correction. Only one of the existing IOCS recommendations covers directly the AE topic, though some non-AE-specific recommendations are also relevant. Those are listed below.

Optically complex waters:

- **2017.04.3**: Apply spectral unmixing approaches to correct for AE from adjacent land/ice (Community, OPEN).
- **2017.07.2**: Develop an atmospheric correction prototype for coastal and inland waters (Community, Actioned)
- **2017.07.3**: Develop a prototype processor to deliver accurate transition from open ocean to coastal and inland waters (Community, Actioned)

Atmospheric correction:

- **2013.02.8**: Aerosol altitude essential for absorbing aerosol (Agencies, Actioned)
- **2019.09.1**: Better understanding of performance of different algorithms (extensive intercomparison) (Community, Actioned)
- **2019.09.3**: Deriving uncertainties when developing new algorithms (Agencies, Actioned)

Uncertainties (in Climate & Carbon and Resolution):

- **2013.09.1**: Uncertainty estimation (Agencies, Actioned)
- **2015.02.2**: Sensitivity analysis to examine the accuracy of retrievals at large sensor and solar zenith angles (Community, OPEN)

New IOCS Recommendations

The gathered community agreed on the following new recommendations defining a roadmap to support the future operational correction of adjacency effects:

- ➔ The community should further develop algorithms for the correction of adjacency effects, which should include *i.* refined capability to account for atmospheric optical properties and off-nadir view, *ii.* capability to account for water surface reflectance anisotropy, *iii.* evaluation of algorithm uncertainties.
- ➔ The community should collect reference in-situ measurements for the validation of adjacency effects correction algorithms (i.e., over small or narrow water bodies, and near-to-the-shore in coastal waters and large inland water basins).
- ➔ The space agencies should support the further development and validation of adjacency effects correction algorithms.
- ➔ The space agencies and IOCCG should promote intercomparison exercises of adjacency effects correction algorithms with reference in-situ data and potentially with synthetic data.
- ➔ The community should develop flags identifying satellite data pixels potentially contaminated by adjacency effects.