



Atmospheric correction of ENVISAT/MERIS data over inland waters: Validation for European lakes

Luis Guanter^{a,f,*}, Antonio Ruiz-Verdú^b, Daniel Odermatt^c, Claudia Giardino^d, Stefan Simis^e, Víctor Estellés^f, Thomas Heege^g, Jose Antonio Domínguez-Gómez^h, Jose Moreno^f

^a GFZ German Research Centre For Geosciences, Telegrafenberg, D-14473 Potsdam, Germany

^b National Institute for Aerospace Technology (INTA), Ctra Ajalvir, km 4.500, 28850 Torrejón de Ardoz, Spain

^c Remote Sensing Laboratories (RSL), Dept. of Geography, University of Zurich, Winterthurerstr. 190, CH-8057 Zurich, Switzerland

^d CNR-IREA, Via Bassini 15, 20133 Milano, Italy

^e Finnish Environment Institute (SYKE), Marine Research Centre, PO BOX 140, FI-00251, Helsinki, Finland

^f Department of Earth Physics and Thermodynamics, University of Valencia, Dr Moliner 50, 46100 Burjassot, Valencia, Spain

^g EOMAP GmbH & Co. KG, Sonderflughafen Oberpfaffenhofen, D-82205 Gilching, Germany

^h Centre for Hydrographic Studies, CEDEX, Pº Bajo de la Virgen del Puerto, 3, 28005 Madrid, Spain

ARTICLE INFO

Article history:

Received 6 May 2009

Received in revised form 28 September 2009

Accepted 2 October 2009

Keywords:

MERIS

Atmospheric correction

Inland waters

Aerosol optical thickness

SCAPE-M

Validation

ABSTRACT

Traditional methods for aerosol retrieval and atmospheric correction of remote sensing data over water surfaces are based on the assumption of zero water reflectance in the near-infrared. Another type of approach which is becoming very popular in atmospheric correction over water is based on the simultaneous retrieval of atmospheric and water parameters through the inversion of coupled atmospheric and bio-optical water models. Both types of approaches may lead to substantial errors over optically-complex water bodies, such as case II waters, in which a wide range of temporal and spatial variations in the concentration of water constituents is expected. This causes the water reflectance in the near-infrared to be non-negligible, and that the water reflectance response under extreme values of the water constituents cannot be described by the assumed bio-optical models. As an alternative to these methods, the SCAPE-M atmospheric processor is proposed in this paper for the automatic atmospheric correction of ENVISAT/MERIS data over inland waters. *A-priori* assumptions on the water composition and its spectral response are avoided by SCAPE-M by calculating reflectance of close-to-land water pixels through spatial extension of atmospheric parameters derived over neighboring land pixels. This approach is supported by the results obtained from the validation of SCAPE-M over a number of European inland water validation sites which is presented in this work. MERIS-derived aerosol optical thickness, water reflectance and water pigments are compared to *in-situ* data acquired concurrently to MERIS images in 20 validation match-ups. SCAPE-M has also been compared to specific processors designed for the retrieval of lake water constituents from MERIS data. The performance of SCAPE-M to reproduce ground-based measurements under a range of water types and the ability of MERIS data to monitor chlorophyll-*a* and phycocyanin pigments using semiempirical algorithms after SCAPE-M processing are discussed. It has been found that SCAPE-M is able to provide high accurate water reflectance over turbid waters, outperforming models based on site-specific bio-optical models, although problems of SCAPE-M to cope with clear waters in some cases have also been identified.

© 2009 Elsevier Inc. All rights reserved.

1. Introduction

The application of remote sensing tools to ocean color monitoring and water quality analysis has increased in the last years following the growing availability of instruments providing the proper radiometric and spectral configuration for water studies. The Coastal Zone Color

Scanner (CZCS) (Hovis et al., 1980) and the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) (McClain et al., 2004) are examples of Earth Observation projects that have been dedicated to water monitoring in the last two decades. The Moderate Resolution Imaging Spectroradiometer (MODIS) (Salomonson et al., 1989), on board the Terra and Aqua platforms, also presents spectral channels devoted to ocean color monitoring. In this context, the MEdium Resolution Imaging Spectrometer (MERIS) (Rast et al., 1999) on board the ENVironmental SATellite (ENVISAT) platform is a multispectral instrument intended to succeed CZCS, SeaWiFS and MODIS as a reference instrument for satellite-based studies of ocean and continental waters.

* Corresponding author. Department of Earth Physics and Thermodynamics, University of Valencia, Dr Moliner 50, 46100 Burjassot, Valencia, Spain.

E-mail address: luisguan@gfz-potsdam.de (L. Guanter).

MERIS is a pushbroom imaging spectrometer operating in the visible and near-infrared (VNIR) spectral range from 400 to 900 nm. It has a field of view (FOV) of 68.5° around nadir, which leads to a swath width of 1150 km at a nominal altitude of 800 km. Ground sampling distance is about 300 m for full spatial resolution (FR) data and about 1.2 km for reduced spatial resolution (RR) data. MERIS is designed to measure with high radiometric performance (noise <2% of the detected signal), high dynamic range (up to 100% albedo) and low sensitivity to polarization (<0.3%) at 15 programmable bands which are set by default to nominal center wavelengths of 412.5, 442.5, 490, 510, 560, 620, 665, 681, 709, 754, 761, 779, 865, 890 and 900 nm with typical bandwidths of 10 nm. One of the major reasons for this wavelength configuration is its sensitivity to the most important optically-active water constituents. For example, retrieval of yellow substances (coloured dissolved organic matter and detritus) (412.5 nm), chlorophyll absorption (442.5, 490, and 665 nm), turbidity (510, 620 nm), red tides (510 nm), and chlorophyll fluorescence (665, 681, and 709 nm) are applications foreseen for MERIS.

Most approaches to the remote sensing of water constituents employ water reflectance data as a starting point. Water reflectance derived from remote sensing data results from the so-called atmospheric correction process, which converts the top-of-atmosphere (TOA) radiance signal into water leaving reflectance after normalization by illumination conditions and removal of atmospheric effects. Aerosol scattering is known to be the largest source of uncertainty in the retrieval of water reflectance from TOA radiance in the VNIR range (Gordon and Wang, 1978, 1994; Wang, 2007), once the contribution from other variables such as illumination and observation conditions and surface elevation can be accurately estimated from ancillary data and radiative transfer models. Assuming the intrinsic temporal and spatial variability of aerosol content, the most accurate atmospheric correction requires aerosol loading over the imaged area to be retrieved for each data acquisition. The reflectance data calculated from atmospheric correction are then used together with analytical or empirical bio-optical models to retrieve water constituents by inversion procedures (Gitelson et al., 2007, 2008; Giardino et al., 2007).

Traditional algorithms for aerosol retrieval over water targets are based on the assumption of zero reflectance in the near-infrared (NIR) spectral region (wavelengths longer than 700 nm) (Gordon and Wang, 1978; Viollier et al., 1980; Gordon and Wang, 1994). However, it has been demonstrated that this approach leads to considerable errors in the presence of absorbing aerosols (Gordon, 1997; Bailey and Werdell, 2006) or over case II waters, where suspended sediments or high concentrations of phytoplankton and detrital particles may originate a non-negligible reflectance at NIR channels (Dekker et al., 1997; Lavender et al., 2005; Morel and Bélanger, 2006). In turn, this NIR reflectance is unknown until an estimate of the aerosol extinction is available, which generates a circular problem. Attempts to correct for non-dark reflectances at NIR in aerosol retrieval over water using simple reflectance models have been published (Siegel et al., 2000; Ruddick et al., 2000). Gao et al. (2007) presented an approach for atmospheric correction of MODIS data over coastal waters based on aerosol retrieval from wavelengths larger than 860 nm, where the contribution of suspended particles and bottom scattering is supposed to be a minimum. Other approaches perform simultaneous retrieval of atmospheric and water components by a multi-parameter inversion using the complete VNIR information and coupled atmospheric and bio-optical radiative transfer models so that aerosol and water parameters are retrieved in a consistent way (Moore et al., 1999). This inversion is normally performed by non-linear optimization (Kuchinke et al., 2009) or neural network (Schiller and Doerffer, 2005; Schroeder et al., 2007; Kratzer et al., 2008) techniques. These methods are very adequate for the representation of the coupled water-atmosphere radiative transfer problem, and are able to provide a

pixel-wise description of the horizontal variations in atmosphere and water. However, these methods may be typically site-specific, as the inversion results depend on the input values applied to constrain the bio-optical model (Kuchinke et al., 2009; Odermatt et al., 2008a). This situation is especially problematic under extreme water turbidity or unusual concentrations of the water constituents, as the bio-optical model is frequently not prepared to deal with those conditions.

A different approach for water reflectance retrieval from MERIS data over continental water bodies is proposed in this work. It is based on a modular approach in which aerosol loading and water reflectance are retrieved sequentially. The processing is carried out by the Self-Contained Atmospheric Parameters Estimation for MERIS data (SCAPE-M) automatic atmospheric correction processor (Guanter et al., 2007, 2008). Aerosol optical thickness and water vapor maps are derived over land surfaces, and extended to medium and small size water targets by spatial interpolation. Aerosol optical thickness over water bodies is then determined from neighboring land surfaces, preferably over dark vegetation. No *a-priori* assumption is made on the water composition and no bio-optical model is necessary for water reflectance retrieval, but water reflectance is derived in parallel to land surface reflectance. Errors in aerosol retrieval due to adjacency effects in the NIR wavelengths, which are expected for medium and small continental water bodies, are also avoided by this methodology. A similar idea for the atmospheric correction of SeaWiFS and MERIS data over inland waters based on aerosol retrieval over land was proposed by Vidot and Santer (2005) and Floricioiu and Rott (2005). The main difference of those approaches to the one presented in this paper is that aerosol retrieval in their work is performed on a per-pixel basis using dense dark vegetation (DDV) pixels. The applicability of those methods is therefore determined by the presence of DDV pixels. SCAPE-M, in contrast, uses a range of land reflectance spectra to characterize a given area for aerosol retrieval. This approach is expected to improve the spatial coverage of the aerosol product.

The main objective of this contribution is to present these “land-based” methods for aerosol and water reflectance retrieval in the case of inland and coastal waters as a robust alternative to standard pixel-wise and “water-based” aerosol retrieval methods. The proposed method may have a limited application range in terms of spatial coverage, as it can only be used with small and medium sized water bodies, and it can fail in the case of inhomogeneous atmospheric conditions. However, its accuracy in reflectance retrieval over very complex water bodies (shallow waters or highly eutrotrophic lakes) may outperform that of approaches based on the inversion of site-specific bio-optical models which are not prepared to cover these abnormal water conditions. This is demonstrated in this paper by the comparison of SCAPE-M water reflectance data with *in-situ* water reflectance measurements and with results from the MERIS lake water processors implemented in the Basic ERS & Envisat (A)ATSR and MERIS (BEAM) Toolbox (Fomferra and Brockmann, 2005). Extense validation has thus far been lacking when dealing with the land-based atmospheric correction of continental waters.

2. Materials and methods

2.1. SCAPE-M atmospheric correction over land and continental waters

The SCAPE-M method for the retrieval of aerosol loading, water vapor and reflectance from MERIS data and the validation of those products over land are described in detail in Guanter et al. (2007, 2008). SCAPE-M performs automatic cloud screening, aerosol and water vapor retrieval and surface reflectance retrieval sequentially from MERIS Level-1b data over land surfaces and over inland and coastal water pixels. The atmospheric optical parameters needed along the processing are calculated by interpolation from a look-up table (LUT) compiled with the MODTRAN4 atmospheric radiative transfer code (Berk et al., 2003). The Thuillier solar irradiance data

base (Thuillier et al., 2003) attached to MERIS images is used as a reference extraterrestrial solar constant. Elevation and topographic corrections are carried out by the use of a digital elevation model (DEM) projected onto each MERIS image to be processed.

Aerosol retrieval is performed over spatially-integrated windows in order to improve the spatial coverage of the aerosol product. In the default configuration, aerosol optical thickness at 550 nm (AOT550) retrieval is performed at macro-pixels of 30 km × 30 km. For each macro-pixel, a maximum AOT550 threshold is estimated from dark pixels in the area, including inland water targets. Such a threshold is calculated as the maximum AOT which gives non-negative reflectance at the dark pixels after atmospheric correction. This value is refined by the exploitation of those cells with sufficient green vegetation and bare soil pixels. The TOA radiances at 5 land pixels, mix of vegetation and bare soil and with as much spectral contrast as possible, are inverted assuming that surface reflectance can be provided by a linear combination of two endmembers, pure vegetation and bare soil spectra. Endmember abundances and the AOT550 are retrieved concurrently. The retrieval of the aerosol type from image data is not attempted, as the MERIS spectral coverage and sampling were found to be insufficient for the reliable retrieval of aerosol type over land (Santer et al., 2005; Ramon and Santer, 2005). The validity of fixing the aerosol model to rural aerosols for a large proportion of cases is probed in Béal et al. (2007). A default rural aerosol model is chosen instead. Both the number of 5-pixel clusters and the number of vegetation endmembers to be used in the inversion are set by the user, according to computation time criteria. The final steps are to fill-in by interpolation areas with unsuccessful AOT retrieval in the macro-pixel mosaic, and to smoothen the resulting mosaic-like AOT550 map using a cubic convolution method. This approach for AOT retrieval overland differs from that presented in Vidot and Santer (2005), in which AOT retrieval was performed pixel-wise and one free parameter in the AOT inversion accounted for the aerosol model through the Ångström coefficient. No information about the reliability of this methodology for aerosol model estimation has been found in the literature.

A validation exercise comparing SCAPE-M AOT550 retrievals from more than 200 MERIS images with AEROSOL ROBOTIC NETWORK (AERONET) data (Holben et al., 1998) from stations around the world was previously carried out (Guanter et al., 2007, 2008). A high correlation between MERIS-derived and AERONET-derived AOT was generally found. Mean square Pearson's correlation coefficient R^2 values were around 0.75, although some cases with low R^2 (0.337, El Arenosillo station) or very high (0.925, Toulouse, FR data) were also found. A systematic underestimation of MERIS-derived AOT by SCAPE-M with respect to AERONET measurements for AOT550 above 0.4 was detected in most of the sites. Root mean square errors (RMSEs) were about 0.05 in most of the tested cases.

Surface reflectance maps are calculated by SCAPE-M from MERIS radiance data from the generated cloud mask, DEM, illumination and observation angles, terrain normal vector, AOT550 nm and columnar water vapor (CWV) maps per-pixel over land and inland water pixels. A Lambertian surface is assumed in the modelling of radiative transfer effects. This same set up has been applied to the processing of water pixels. The AOT550 and CWV maps derived from land surfaces are extended to inland water targets by spatial inter- or extrapolation. This is implicitly performed by the smoothing of the mosaic of 30 km × 30 km cells in which AOT is retrieved. A spatially-continuous AOT map covering the imaged area is obtained after the smoothing process. Large water pixels non-compliant with the assumption of horizontal continuity of the atmospheric parameters are then screened out of the processing. In the default processing mode, inland water pixels are defined as those water pixels not further than 20 km from a land surface, or those inside closed water bodies with an area of less than 1600 km². These limits are empirically defined as the maximum distance within which the assumption of the continuity of

AOT550 and CWV can normally be assumed. However, since the horizontal continuity of atmospheric parameters depends on changing factors, such as the atmospheric stability or the existence of aerosol sources located close to the water bodies, the 20 km and 1600 km² figures could vary in the real case. For this reason, SCAPE-M presents a supervised processing mode in which the maximum water–land distance and lake area can be set by an assay error approach. The visual inspection of the resulting water reflectance spectra is the main indicator for the selection of those parameters.

The impact of adjacency effects over inland and coastal water pixels can be very strong in the NIR channels, for which water is very dark and land pixels normally present a high reflectance, and can even be noticed in visible channels under certain conditions (Odermatt et al., 2008b). A simple adjacency correction is performed by SCAPE-M on the final reflectance product. It consists in modelling the at-sensor radiance as a linear combination of the photons coming directly from the target and those coming from areas adjacent to the target and scattered into the sensor direction. This is implemented by weighting the strength of the adjacency effect by the ratio of diffuse to direct ground-to-sensor transmittance (Vermeote et al., 1997). The adjacency-corrected surface reflectance, ρ , is then calculated as

$$\rho = \rho^u + \frac{t_{\text{dif}}^{\uparrow}}{t_{\text{dir}}^{\uparrow}} [\rho^u - \bar{\rho}], \quad (1)$$

where ρ^u is the target reflectance before the adjacency correction, $\bar{\rho}$ is the background reflectance, calculated as the distance-weighted average reflectance of the neighboring pixels, and $t_{\text{dir}}^{\uparrow}$, $t_{\text{dif}}^{\uparrow}$ are the atmospheric transmittance functions between the surface and the sensor for direct and diffuse radiation, respectively. The Improved Contrast between Ocean and Land (ICOL) processor (Santer et al., 2009) is implemented in the BEAM software in order to enable adjacency correction of MERIS data at the radiance level. The ICOL processor, which is based on the formulation presented above, will be used as a reference for validation later in this work.

It must be clearly pointed out that SCAPE-M is not a water-oriented atmospheric processor, but a general purpose atmospheric correction method for MERIS data over continental surfaces. The emphasis in SCAPE-M is put on the rigorous modelling of atmospheric effects and the automatic estimation of atmospheric aerosol and water vapor parameters. This is known to be a major issue for the accurate reflectance retrieval, even in the case of water targets. However, this generic nature of SCAPE-M implies that some water-specific aspects, such as the choice of an aerosol model, which cannot be reliably performed from MERIS data over land but it is possible over water, or the consideration of bidirectional reflectance effects at the surface, which may account for about 5% of the water reflectance signal (Park and Ruddick, 2005) are neglected.

2.2. Algorithms for the estimation of phycocyanin and chlorophyll-*a* from MERIS data

The suitability of MERIS data and SCAPE-M processing for the monitoring of water pigments on eutrophic lakes has been explored as a further validation exercise. The concentration of chlorophyll *a* ([CHL-*a*]) from both MERIS- and radiometry-based reflectance data has been calculated using the Gons semiempirical algorithm (Gons, 1999), and the concentration of the cyanobacterial pigment phycocyanin ([PC]) has been calculated using the Simis et al. semiempirical algorithm (Simis et al., 2005, 2007). These algorithms will be referred to as CHL-*a* and PC algorithms hereafter.

Both algorithms were developed for use with turbid waters and are based on reflectance band ratios and semiempirical relationships using MERIS channels at 620, 665, 709 and 778.8 nm. Water and phytoplankton pigments are assumed to dominate absorption in the

620 nm channel (PC and CHL-*a*) and in the 665 nm channel (CHL-*a*), while absorption in the 709 and 779 nm bands is assumed to be dominated by water. Following Gons et al. (2005), a spectrally neutral backscattering coefficient b_b is calculated from the normalized water reflectance (R_w) in the 779 nm channel as

$$b_b(779) = \frac{1.61 \times R_w(779)}{0.082 - 0.6 \times R_w(779)}. \quad (2)$$

Following Gons (1999), Gons et al. (2005), Simis et al. (2005), [CHL-*a*] is calculated from $b_b(779)$ by

$$[CHL - a] = \left[\frac{R_w(709)}{R_w(665)} (0.727 + b_b) - 0.401 - b_b \right] / 0.015. \quad (3)$$

In turn, [PC] is calculated by the nested semiempirical band ratio algorithm described in Simis et al. (2005, 2007). This model uses the same reflectance model in Eq. (3) and corrects for CHL-*a* absorption in the 620 nm:

$$[PC] = 170 \times \left[\frac{R_w(709)}{R_w(620)} (0.727 + b_b) - 0.281 - b_b \right] - (0.51 \times [CHL - a]) \quad (4)$$

These CHL-*a* and PC algorithms have been selected because they can provide a reliable measure of [CHL-*a*] and [PC] in turbid waters by means of simple reflectance relationships, which makes them suitable for an estimation of the impact of atmospheric correction over the subsequent retrieval of water pigment concentrations.

2.3. Lake water processors in the BEAM software

The performance of the SCAPE-M atmospheric processor has been compared to that of the MERIS lake algorithms (Doerffer and Schiller, 2008) implemented in the BEAM software (Fomferra and Brockmann, 2005). These algorithms include neural network-based enhanced atmospheric correction and specific bio-optical algorithms to derive inherent optical properties (IOPs) and water constituents concentration (CHL-*a* and total suspended matter) from MERIS data. Based on specific IOP ranges (CHL-*a*, *gelbstoff* and suspended matter), three different processors are available. The *Case-2 Regional* (C2R) water processor (version 1.3) presents a bio-optical model adapted to a wide range of IOP variation, while the *eutrophic lakes* and the *boreal lakes* processors (version 1.0) share the same architecture, but the bio-optical models were optimized for extreme concentrations of CHL-*a* and *gelbstoff*, respectively. The user of these processors must decide in advance which one is better suited to the data to be processed. The IOPs used for the development of the bio-optical models of the *eutrophic lakes* and the *boreal lakes* were measured in Spanish and Finnish lakes, respectively. Validation of reflectance and water constituents retrieval by these processors is presented in Ruiz-Verdú et al. (2008a).

2.4. In-situ validation data

A set of MERIS FR images acquired over some European sites where concurrent *in-situ* measurements of water reflectance were available was selected and processed with SCAPE-M. Ground-based measurements were acquired during field campaigns devoted to water quality studies, and some of them in support of MERIS activities for algorithm development and validation.

A field campaign directed by the Centre for Hydrographic Studies (CEDEX, Spain) on 19 June 2003 yielded reflectance spectra from several mountain reservoirs in the Northeast of the Iberian Peninsula for the validation of airborne-based and MERIS Level-2 water products. The measurements were made in the deep oligotrophic

Tremp and Canelles reservoirs, in the oligotrophic Rialb reservoir and in the shallow and turbid Terradets reservoir. Radiometric measurements were taken with an ASD-FR spectroradiometer (Analytical Spectral Devices, Boulder, CO USA). The time between the measurements and the ENVISAT overpasses was 1 day at worst.

CEDEX was also involved in a series of 8 campaigns performed in June and July 2007 for the validation of MERIS lake water processors. Four reservoirs and one coastal lake were chosen, covering a wide gradient of environmental conditions: Albufera de Valencia, a hypereutrophic freshwater coastal lagoon, characterized by very high CHL-*a* concentrations ($>250 \text{ mg m}^{-3}$) and frequent cyanobacteria blooms; Almendra, a large, high altitude eutrophic reservoir; Cuerda del Pozo, a medium size, mesotrophic mountain reservoir; Iznájar, a medium size, low altitude, mesotrophic reservoir, and Rosarito, a medium size eutrophic reservoir with high summer CHL-*a* concentrations and persistence of cyanobacteria. Atmospheric measurements were carried out with a CIMEL 318NE sunphotometer (CIMEL Electronique, Paris, France) concurrent to MERIS acquisitions during those campaigns. Technical problems prevented *in-situ* reflectance measurements during one visit to the Almendra reservoir on 27 June 2007.

Spectroradiometric measurements were also acquired at Lake IJsselmeer during MERIS acquisitions in Summer 2004 and 2005 by The Netherlands Institute of Ecology (NIOO-KNAW). Lake IJsselmeer is a large (1200 km^2), turbid (Secchi disk depth 1.0 m), shallow (average depth 4 m) and eutrophic lake system which exhibits a seasonal phytoplankton distribution with summer blooms of mainly chlorophytes and cyanobacteria. Spectroradiometric measurements were collected *in-situ* using a PR-650 (Photo Research Inc, Chatsworth, CA USA) handheld spectroradiometer to measure water leaving radiance, sky radiance, and downwelling irradiance, as described in detail elsewhere (Gons, 1999; Simis et al., 2005, 2007). The reflectance measurements used here were obtained at anchor stations as the average of three reflectance measurements, each consisting of 10 recordings of each (ir)radiance component.

In the northern prealpine region, MERIS coinciding spectroradiometric measurements of Lake Constance, Lake Lemman (also known as Lake Geneva) and Lake Zurich were taken during 4 campaigns in 2007. The campaigns on Lake Constance were carried out for the MERIS Lakes validation project (Ruiz-Verdú et al., 2008a) by a consortium led by EOMAP GmbH, supported by the Institute for Lake Research, Langenargen, Germany, the Limnological Institute of the University of Konstanz, the University of Hohenheim and RSL of the University of Zurich. The data of Lake Lemman and Lake Zurich were measured by RSL, the former with the support of the Lacustrian Hydrobiology Station in Thonon-les-Bains in the case of Lake Lemman. In all campaigns, RAMSES ARC and ASC instruments (TriOS GmbH, Oldenburg, Germany) provided by DLR (German Aerospace Center, Oberpfaffenhofen, Germany) were used to measure downwelling irradiance as well as upwelling radiance and irradiance below the surface, which were subsequently converted into reflectance. Lake Lemman and Lake Constance are the largest two freshwater reservoirs in Western Europe, with a total area of 580 and 535 km^2 , and an average depth of 310 and 254 m, respectively. Lake Zurich is considerably smaller (88 km^2 , 136 m). The three lakes are situated in the Rhone, Rhine and Linth Valleys, respectively, which drain the Northern Prealps in northern to western directions. In 2006, *in-situ* measured concentrations of CHL-*a* in the 0–20 m zone varied from 1.5 to 10.0 mg m^{-3} in Lake Lemman and from 0.5 to 5.7 mg m^{-3} in Lake Constance. The variations in Lake Zurich in 2007 were between 3.2 and 17.7 mg m^{-3} . Lake Constance is thus considered oligotrophic, Lake Lemman is mesotrophic and Lake Zurich is between meso- and eutrophic.

A series of field studies were conducted in summer 2008 by the Institute for Electromagnetic Sensing of the Environment of the National Research Council of Italy (CNR-IREA) at the Italian lakes of

Trasimeno, Maggiore and Garda. Lake Garda and Lake Maggiore are the two largest lakes of Italy, with a size of 368 km² and of 212 km², respectively. Both located in the northern part of the country, they belong to the subalpine ecoregion and are part of the most important Italian lacustrine district, which represents about 80% of the total Italian lacustrine volume. Maggiore and Garda lakes are very deep (average depth of 178 m and 133 m, respectively) and oligotrophic, although Lake Garda shows some tendency towards mesotrophic conditions. Lake Trasimeno, the fourth largest Italian lake (124 km²), is located in central Italy. It is a shallow (average depth of 4 m) and mesotrophic lake, characterized by turbid waters (average Secchi disk depth 1 m). A total of 10 stations were measured in Lake Trasimeno on 6 August and 23 September 2008, synchronous with MERIS acquisitions. Two stations were sampled on 6 May 2008 in southern Lake Garda in coincidence of MERIS, then 12 stations were measured on 3 August 2008 in Lake Maggiore. At each station, water reflectance data were derived by underwater downwelling irradiance and upwelling radiance ASD-FR measurements, subsequently corrected for the emersion factor.

After screening cloud and sun-glint contaminated images, a total of 20 match-ups between field and MERIS measurements were available for water reflectance spectra validation, and 6 for AOT retrieval. An overview of the European validation sites used in this study is given in Table 1, and a summary of the corresponding field campaigns is provided in Table 2. The spatial distribution of the Secchi disk and CHL-*a* average values given in the table may vary substantially for some of the lakes. In particular, CHL-*a* values of up to 130 mg m⁻³ were measured in Lake IJsselmeer, and values of the Secchi disk between 1.5 and 7.5 m have been measured in Lake Constance. Lakes and reservoirs in Table 2 were arbitrarily considered as turbid for the present work when the Secchi disk was below 3 m. The geographic distribution of the validation sites is depicted in Fig. 1. A concentration of sites in subalpine regions and in the Iberian Peninsula can be observed.

3. Results

3.1. Results from AOT retrieval

The comparison between CIMEL and MERIS-derived AOT550 from the CEDEX 2007 validation campaigns is displayed in Fig. 2. The same comparison is also plotted for water vapor. Error bars refer to the *a-priori* estimated uncertainty of CIMEL and MERIS AOT550 and CWV retrievals. A good correlation between field data and MERIS is found for both AOT550 and CWV. In the case of AOT, which is the most important atmospheric parameter to be considered for water

Table 2

Summary of the validation campaigns with field activities concurrent to MERIS acquisitions used in this study.

Campaign	Date (ddmmyy)	<i>t</i> , MERIS (hh:mm)	Δt , <i>In-situ</i> (hh:mm)	Secchi (m)	CHL- <i>a</i> (mg m ⁻³)
Albufera	06-06-07	10:11	10:00–11:20	0.2	379.0
Almendra I	27-06-07	10:50	N/A	2.4	44.0
Almendra II	10-07-07	10:42	10:10–11:20	1.8	44.0
Canelles	17-06-03 ^a	10:20	10:30–12:05	6.0	1.0
Constance I	13-04-07	10:06	8:10–10:40	3.9	2.7
Constance II	20-04-07	9:46	8:20–11:05	5.4	1.7
Cuerda del Pozo	28-06-07	10:19	12:10–12:30	3.2	4.0
Garda	06-05-08	9:40	12:13–12:45	8.0	2.7
IJsselmeer I	03-08-04	9:58	9:00–15:30	1.0	35.9
IJsselmeer II	07-09-04	9:58	8:30–16:15	1.0	69.1
IJsselmeer III	16-08-05	10:18	8:40–15:30	1.0	61.5
Iznájar	04-07-07	10:31	9:50–11:10	4.8	1.4
Leman/Geneva	10-09-07	9:52	10:40–11:07	>3.0	3.0
Maggiore	03-08-08	9:43	9:00–14:22	>3.0	N/A
Rialb	18-06-03 ^a	10:20	10:00–11:10	2.0	8.7
Rosarito	13-07-07	10:48	10:20	0.5	53.0
Terradets	18-06-03 ^a	10:20	15:45–16:10	0.6	0.9
Trasimeno I	06-08-08	9:49	10:41–12:06	1.0	5.0
Trasimeno II	23-09-08	9:40	9:30–12:12	1.0	5.0
Tremp	19-06-03	10:20	8:55–10:50	4.6	2.4
Zurich	15-08-07	10:09	12:30–13:16	<3.0	10.0

Secchi disk and CHL-*a* values are not fully representative for lakes with high spatial and temporal variations. Data acquisition times are given in the UTC scale.

^a MERIS data were acquired on 19-06-03.

reflectance retrieval, the calculated $R^2 = 0.74$ and $RMSE = 0.07$ values are in agreement with those derived from the validation exercise previously performed over AERONET sites (Guanter et al., 2008), where more points were available for statistical analysis. The worst SCAPE-M performance is found at the Iznájar site. This can be explained by the absence of green vegetation targets in the surroundings of the Iznájar reservoir, located in the Southern Iberian Peninsula, to serve as a basis for aerosol retrieval. Only bright soils and semi-arid areas are present around Iznájar instead. Even though SCAPE-M is expected to provide a better spatial coverage than DDV-based aerosol retrieval algorithms, the presence of at least a number of dark or semi-dark surfaces in the study area is necessary for the reliable aerosol retrieval. On the other hand, the presence of aerosol particles with optical properties different from those parameterized by the default rural aerosol model cannot be discarded as an error source for this area either.

Table 1

Summary of the validation sites used in this study.

Site	Lat/Lon (°N, °E)	Institution	Instruments	Description
Albufera	39.4, -0.3	CEDEX	ASD, CIMEL	Hypereutrophic
Almendra	41.2, -6.3	CEDEX	ASD, CIMEL	High altitude, eutrophic
Canelles	42.1, 0.6	CEDEX	ASD	Deep, oligotrophic
Constance	47.5, 9.7	RSL&EOMAP	RAMSES	Large, oligotrophic
C. del Pozo	41.9, -2.7	CEDEX	ASD, CIMEL	Mountain, mesotrophic
Garda	45.6, 10.5	CNR-IREA	ASD	Deep, oligotrophic
IJsselmeer	52.7, 5.4	NIOO-KNAW	PR-650	Eutrophic, summer blooms
Iznájar	37.3, -4.3	CEDEX	ASD, CIMEL	Low altitude, mesotrophic
Leman	46.4, 6.5	RSL&EOMAP	RAMSES	Large, mesotrophic
Maggiore	45.9, 8.5	CNR-IREA	ASD	Deep, oligotrophic
Rialb	42.0, 1.2	CEDEX	ASD	Oligotrophic
Rosarito	40.0, -5.1	CEDEX	ASD, CIMEL	Eutrophic, high CHL- <i>a</i>
Terradets	40.1, 0.9	CEDEX	ASD	Turbid, shallow
Trasimeno	43.1, 12.1	CNR-IREA	ASD	Shallow, mesotrophic
Tremp	42.2, 0.9	CEDEX	ASD	Deep, oligotrophic
Zurich	47.4, 8.6	RSL&EOMAP	RAMSES	Small, meso-/eutrophic

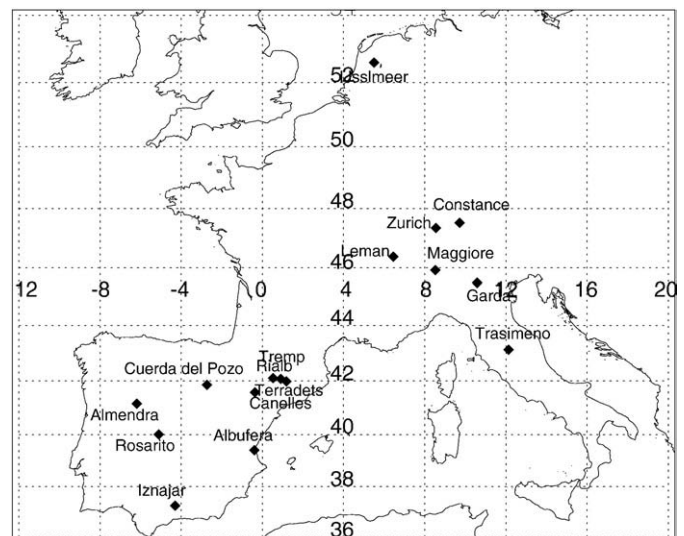


Fig. 1. Geographic distribution of validation sites.

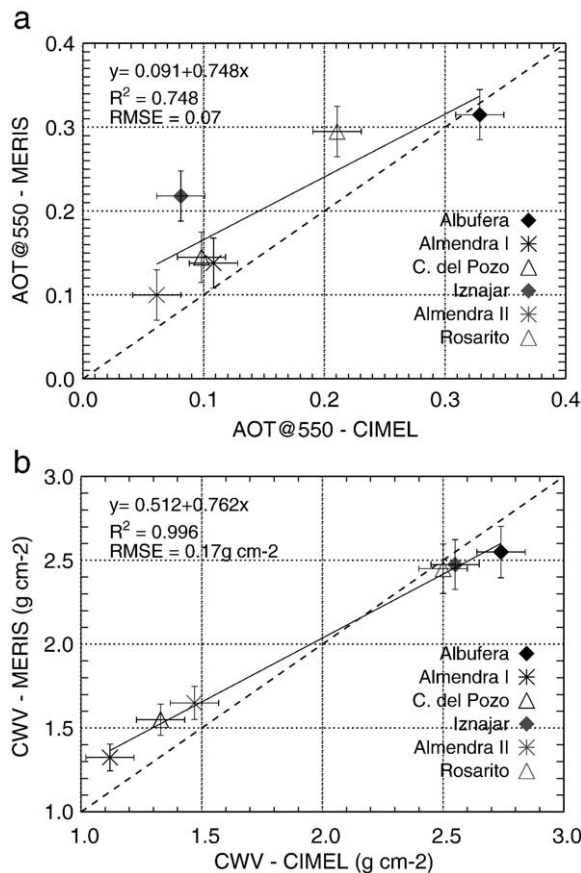


Fig. 2. Comparison between CIMEL- and SCAPE-M derived aerosol optical thickness at 550 nm (a) and columnar water vapor (b) from CEDEX 2007 field campaigns. Error bars show the *a-priori* estimated uncertainty of MERIS and CIMEL retrievals.

A high accuracy in SCAPE-M CWV retrieval is confirmed. The R^2 coefficient grows to 0.996 in the comparison between CIMEL and MERIS-based CWV. Even though water vapor has a lower impact on water reflectance retrieval than AOT, the small errors found in MERIS-derived CWV confirm the proper modelling of the atmospheric effects performed by SCAPE-M.

3.2. Results from reflectance retrieval

Remote sensing reflectance (R_{rs}) spectra calculated by SCAPE-M from MERIS data are compared to field measurements acquired at Spanish lakes and reservoirs during the CEDEX 2003 and 2007 field campaigns in Fig. 3. $R_{rs}(\lambda)$ is defined as the ratio between the above water leaving radiance and the incoming irradiance flux at wavelength λ . In the case of the MERIS-based reflectance spectra, $R_{rs}(\lambda)$ mean values were calculated from spatial averaging of 3×3 -pixel windows in the MERIS images. In the case of *in-situ* measurements, all the reflectance spectra available for each validation site were averaged. Error bars correspond to the standard deviation of these data, and indicate the spatial variability at either MERIS or ground scales. A very good reconstruction of both overall brightness and spectral shape is achieved in all cases. The worst results in Fig. 3 were found for the Cuerda del Pozo reservoir in Fig. 3(h), where low reflectance in the NIR channels was not well retrieved from the SCAPE-M processing of MERIS images. This could be explained by residual adjacency effects or a bad parameterization of the aerosol spectral extinction associated to a wrong aerosol model. The deviation of the default aerosol profile from the actual, unknown, aerosol profile has also been proposed as a considerable error source in reflectance retrieval over clear water (Gordon, 1997; Duforêt et al., 2007).

Further comparison between MERIS-derived R_{rs} spectra and field radiometry for lakes in Italy (Trasimeno, Garda and Maggiore), Switzerland (Zurich and Leman), Germany (Constance) and The Netherlands (IJsselmeer) is displayed in Fig. 4. Mean and standard deviation from a series of pixels or measurements are again plotted as dots and error bars to indicate spatial variability. Because of the large area and the high variability in water composition of Lake IJsselmeer, only three representative spectra from three campaigns in summer 2004 and 2005 are displayed. It can be observed that the good comparison between MERIS and ground reflectance retrievals stated in the Spanish lakes in Fig. 3 is again obtained in the Trasimeno, Zurich and IJsselmeer turbid lakes, while neither the overall brightness nor the spectral shape of the reference ground measurements can be reconstructed from the MERIS data processed with SCAPE-M over the subalpine lakes Garda, Maggiore, Leman and Constance. The water turbidity in the subalpine lakes has been classified as clear or very clear. Especially in Lake Garda and Lake Maggiore, the water leaving radiance at the TOA is comparable to the instrument noise equivalent radiance (NER) which defines the instrument sensitivity and noise levels (R. Doerffer, GKSS Research Centre, personal communication, 2008). In the case of Lake IJsselmeer, MERIS-derived reflectance spectra match both the overall reflectance levels and spectral shape of the *in-situ* measurements, apart from wrong reflectance values at the blue channels resulting from undercorrected atmospheric effects, most probably aerosols or unmasked cirrus clouds.

For low water reflectance, an accurate parameterization of aerosol extinction becomes mandatory. Errors in AOT550, aerosol model scattering and absorption characteristics or aerosol vertical profile would lead to strong errors in the retrieved water reflectance. Simulations with MODTRAN4 were used to further research this issue. A very dark water pixel extracted from a MERIS image acquired on 13 April 2007 over Lake Constance was atmospherically corrected under different combinations of AOT550 values, between 0.05 and 0.7, and the rural, maritime and urban models. The real illumination and observation angles and surface elevation were fed into the simulations. It was found that there was no combination of aerosol loading and model which could retrieve a R_{rs} spectrum comparable to the one measured in the field. Undercorrected spectra, with a maximum reflectance in the blue, or negative values were derived from most of the tested combinations. According to these results, the inability of SCAPE-M to derive a correct reflectance spectrum will not be partially or totally associated to aerosol retrieval, but also to other factors such as the unavailability of a suitable aerosol model in the MODTRAN4 data base should be considered. Thin cirrus clouds were detected over Lake Constance on 13 April 2007, which could explain the undercorrection of the reflectance spectra in Fig. 4. However, the same undercorrection trends in the blue wavelengths are observed in data from 20 April 2007, when clear-sky conditions were reported, and very similar results were found by Vidot and Santer (2005) using SeaWiFS data acquired over Lake Constance in 2000 and 2001, and by Fomferra and Brockmann (2005) over Lake Garda. This would support the idea that pure physically-based atmospheric correction approaches and standard aerosol models cannot reliably handle data acquired under certain atmospheric conditions from very dark water. Adjacency effects, not simulated in the one-pixel analysis, or a wrong aerosol vertical profile, as suggested by Gordon (1997) and Duforêt et al. (2007), could explain retrieval errors in this worst case of very clear waters. Sun glint contamination is in principle discarded because of the low view zenith angle of 9° and mild wind conditions. The inability of SCAPE-M to cope with those cases in some conditions is considered one of the limitations of the method. Site-specific processing methods could give better results over this kind of target (Odermatt et al., 2008a).

Potential differences in atmospheric conditions between the Iberian Peninsula and the subalpine regions are in principle not considered to explain the different performance of SCAPE-M at those

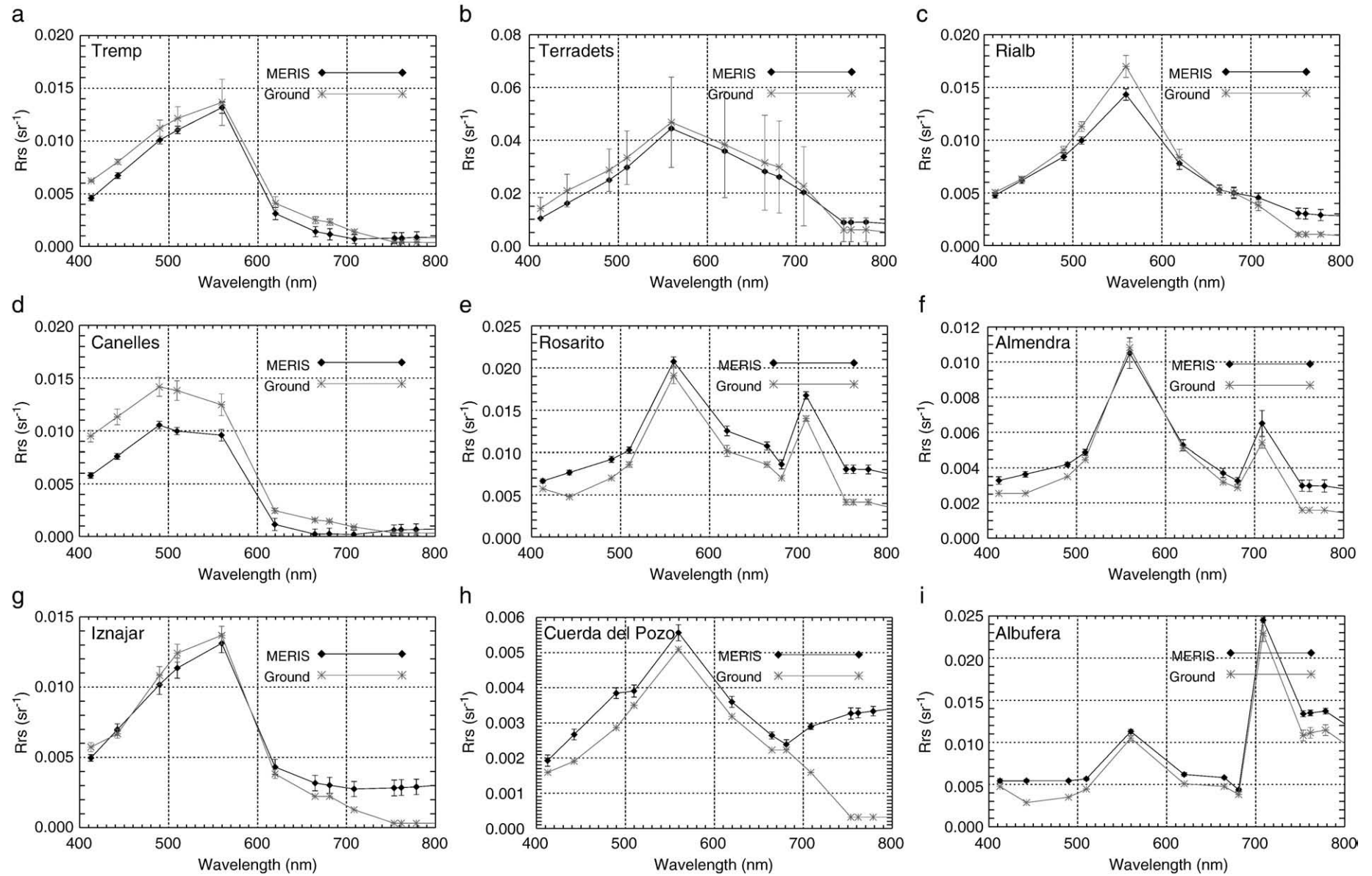


Fig. 3. Comparison between *in-situ* and SCAPE-M remote sensing reflectance spectra from lakes and reservoirs of the Iberian Peninsula from the CEDEX 2003 and 2007 field campaigns. Error bars refer to the standard deviation calculated from all the measurements available for a given lake.

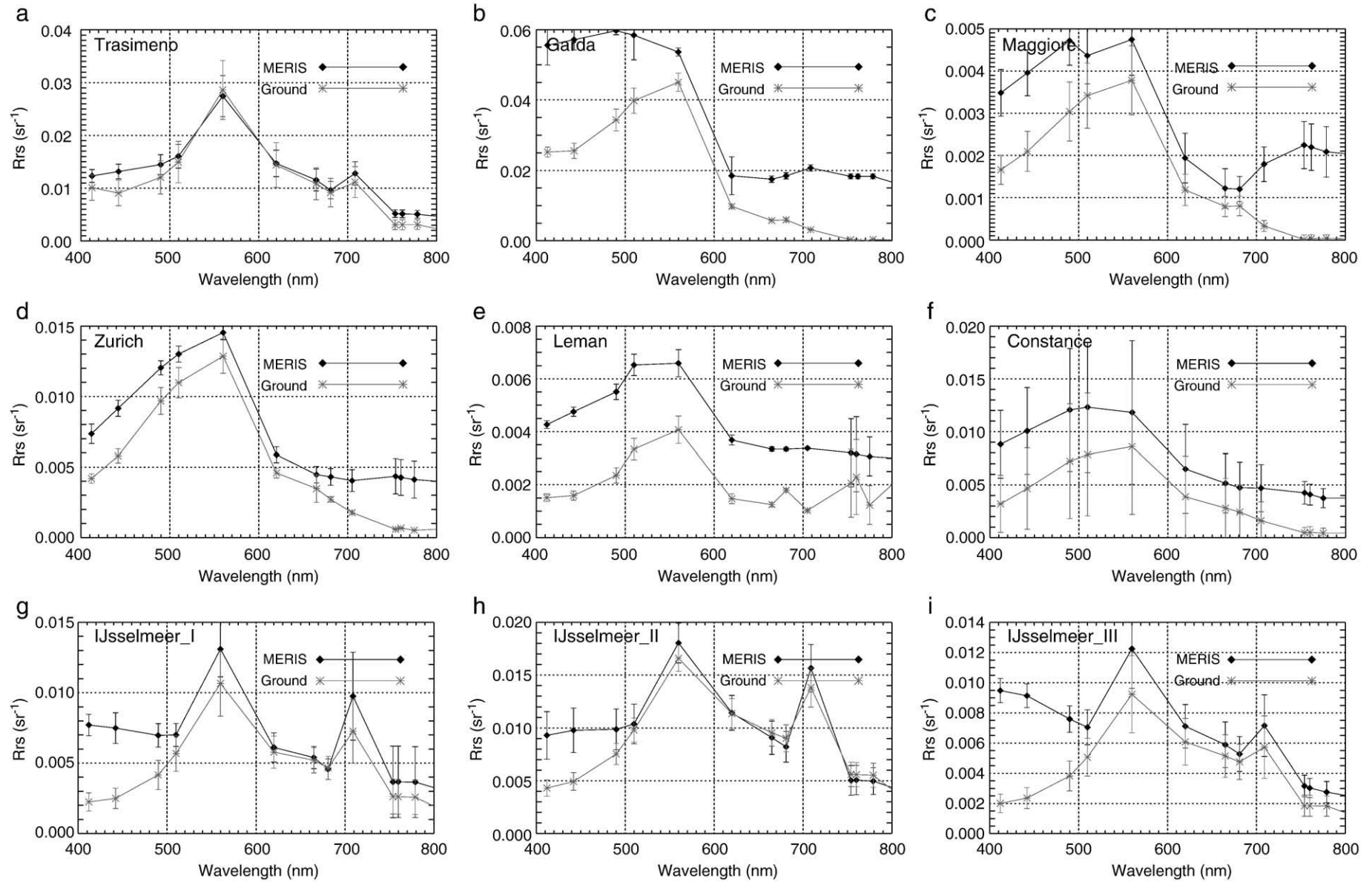


Fig. 4. Comparison between *in-situ* and SCAPE-M remote sensing reflectance spectra from lakes in Italy (Trasimeno, Garda and Maggiore), Switzerland (Zurich and Leman), Germany (Constance) and The Netherlands (IJsselmeer). Error bars refer to the standard deviation calculated from all the measurements available for a given lake.

sites. Even though clear-sky weather conditions are expected in the Iberian Peninsula more often than in the subalpine areas, desert dust or maritime aerosols intrusions are also expected, which gives as a result a high variety of aerosol concentration and type. Moreover, most of the Spanish lakes and reservoirs in Fig. 3 are located on a plateau at about 600–700 m above sea level, which is comparable to the elevation of subalpine lakes. On the other hand, differences in the MERIS and *in-situ* acquisition times are in principle not considered a major error source in reflectance retrieval. Even though optically-complex waters may change their spectral response in short time lapses, no correlation between time difference and reflectance errors can be deduced from Figs. 3, 4 and Table 2.

3.3. Comparison of reflectance derived from SCAPE-M and BEAM processors

SCAPE-M atmospheric correction performance was also compared to that of the MERIS lake algorithms (Doerffer and Schiller, 2008)

implemented in the BEAM Toolbox (Fomferra and Brockmann, 2005). Reflectance spectra derived by SCAPE-M from MERIS data over some of the validation sites in Table 1 that were considered representative for the whole data set are plotted with *in-situ* measurements and the results obtained from BEAM processors in Fig. 5. Data over Lake Albufera and Rosarito reservoir were processed by the *eutrophic lakes* processor, and the rest was processed by the combined application of the Improved Contrast between Ocean and Land (ICOL) processor (Santer et al., 2009), also implemented in BEAM, and the C2R processor, as suggested by Giardino et al. (2008) and Odermatt et al. (2008b). ICOL is applied to the input radiance data in order to correct for adjacency effects at the radiance level. A different performance of SCAPE-M and the BEAM processors as a function of the water spectral response can be observed. SCAPE-M provided a better agreement with the reference ground-based reflectance in the case of turbid waters with high reflectance levels, while the BEAM processors performed better over dark waters. In the case of Lake Albufera, the reflectance

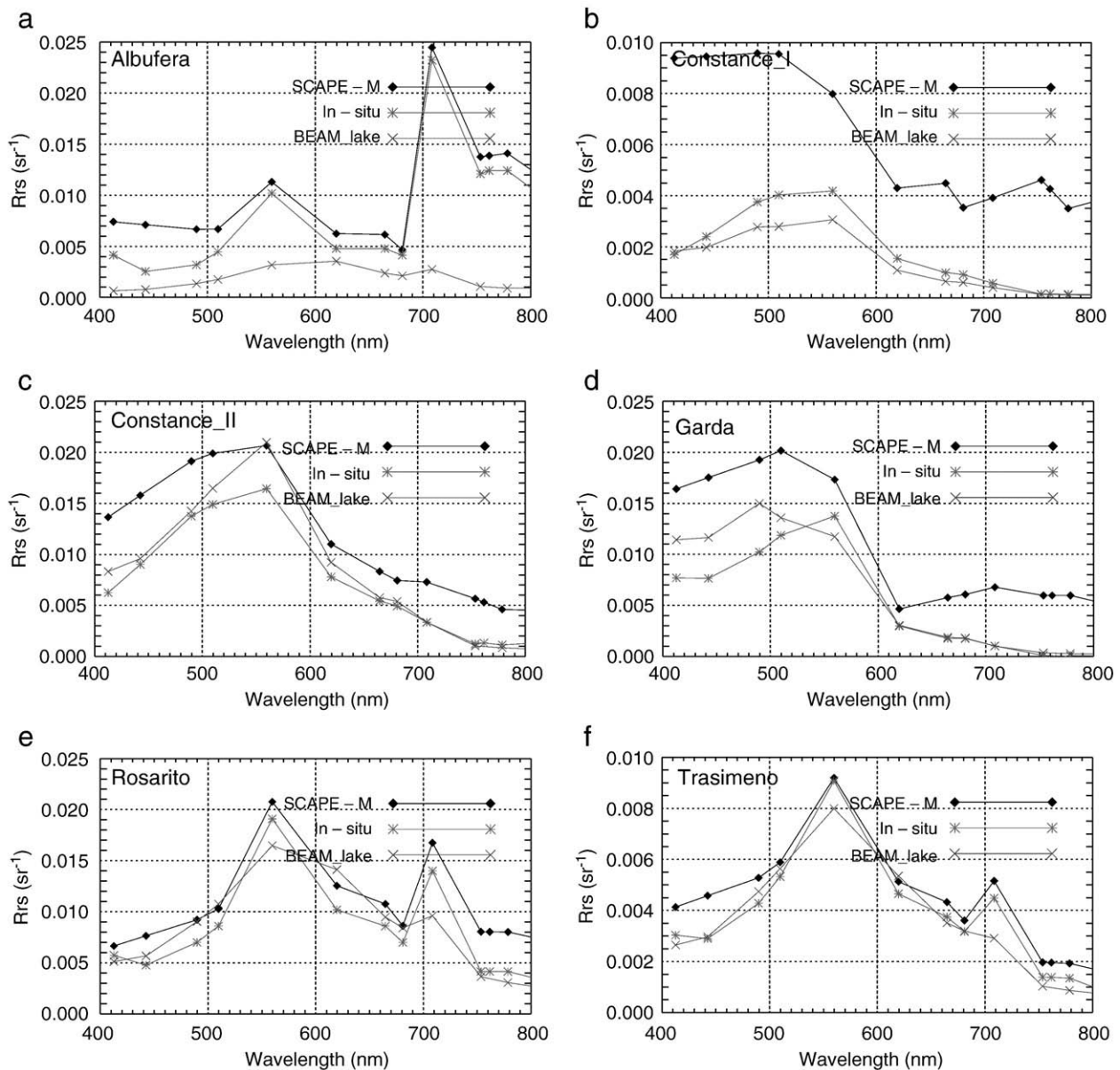


Fig. 5. Comparison between reflectance spectra calculated by SCAPE-M and the BEAM lake processors. All the data were processed by ICOL and C2R processors in BEAM, except for Lake Albufera and Lake Rosarito, to which the *eutrophic lakes* processor was applied.

spectrum derived by the BEAM processor is far from the reference measurement. This can be explained by the very high CHL-*a* concentration in the lake, that caused the *eutrophic lakes* processor to be out of its application range, despite the fact that it was optimized for high eutrophic conditions. In the case of Lake Rosarito and Lake Trasimeno, both methods are giving a reflectance level comparable to *in-situ* data, but only SCAPE-M R_{rs} spectra can accurately reproduce the spectral shape in the 500–750 nm window, where the most useful information about water composition is contained. However, SCAPE-M is not able to reproduce the low reflectance levels in Lake Constance (station I) and Lake Garda, as discussed in the previous section. ICOL and C2R processors are performing better in this case in terms of overall brightness, even though the spectral shape of the reflectance spectrum from Lake Garda is not well retrieved either. Both algorithms present a comparable performance over the intermediate case of Lake Constance, station II, where the water signal is stronger than in station I.

It can be concluded from this comparison that physically-based algorithms inverting surface reflectance from TOA radiance by means of the explicit formulation of atmospheric radiative transfer processes and AOT retrieval have a wider application range than those based on multi-parameter inversion and specific training data bases like neural networks. This is clear in the case of Lake Albufera, where the extreme CHL-*a* concentrations render algorithms based on specific IOPs inapplicable. On the other hand, neural networks and multi-parameter inversion seem to compensate for potential errors in the atmospheric characterization over very dark water, and are then able to provide a higher accuracy in reflectance retrieval. Those trends were found in most of the data sets over which a similar comparison between SCAPE-M and BEAM processors was performed.

3.4. Validation of phytoplankton pigments derived from MERIS data after SCAPE-M processing

Results from [CHL-*a*] and [PC] pigment retrieval from *in-situ* and from SCAPE-M reflectance at Lake IJsselmeer using the CHL-*a* and PC algorithms presented in Section 2 are plotted in Fig. 6. It must be noted that the PC algorithm was parameterized using these data as part of a larger dataset, so they are not fully statistically independent. Input reflectance data were acquired at Lake IJsselmeer during three different campaigns on August and September 2004 and August 2005, which were used to generate the mean reflectance spectra displayed in Fig. 4. The large range of pigment concentrations at Lake IJsselmeer can be observed. Apart from a systematic overestimation of CHL-*a* and PC from SCAPE-M with respect to field radiometry, a high correlation between MERIS and radiometry-based CHL-*a* and PC is found, with correlation coefficients of $R^2 = 0.75$ and $R^2 = 0.83$, respectively. This confirms that errors in overall reflectance brightness can be minimized at the data exploitation step by band rationing-like approaches like that of the CHL-*a* and PC algorithms, at least over bright (turbid) targets. The results in Fig. 6 state that an accurate retrieval of spectral reflectance patterns can lead to a good characterization of water constituents even with errors in the overall reflectance absolute values.

The comparison of the CHL-*a* derived from MERIS data and field radiometry with CHL-*a* values calculated in the laboratory from Lake IJsselmeer samples acquired during the same campaigns is depicted in Fig. 7. Taking laboratory measurements as a reference, it can be concluded that changes in CHL-*a* can be monitored by the CHL-*a* algorithm using both MERIS and field radiometry measurements. The correlation coefficient calculated from radiometry-based CHL-*a* is $R^2 = 0.59$ and the RMSE of 19 mg m^{-3} . These values become

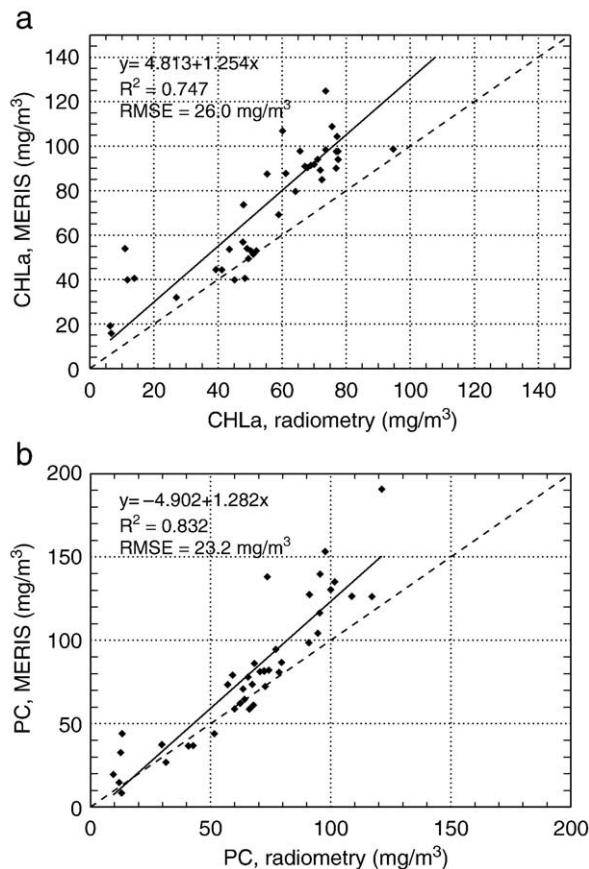


Fig. 6. Comparison between (a) CHL-*a* and (b) PC, derived from SCAPE-M and field spectroradiometry data from the Lake IJsselmeer study site.

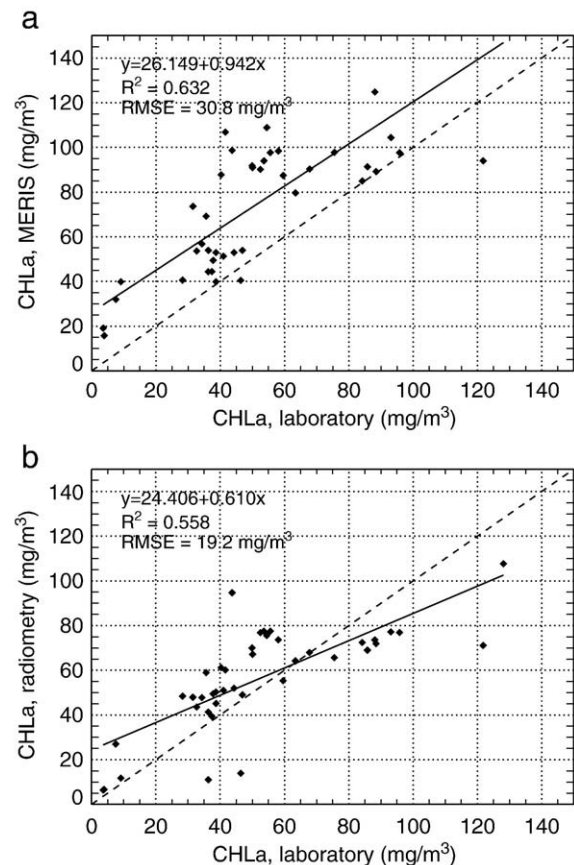


Fig. 7. Comparison of CHL-*a* derived from (a) SCAPE-M data and (b) field spectro-radiometry with laboratory pigment extracts, for the Lake IJsselmeer study site.

$R^2 = 0.63$ and $RMSE = 30 \text{ mg m}^{-3}$ when the comparison is performed between MERIS and laboratory CHL-*a*. Apart from errors associated to atmospheric correction, differences in CHL-*a* between laboratory and MERIS and radiometry data can also be partially explained by the fact that water sampling depth for laboratory analysis may be different from the depth of the water column whose signal is sensed both by MERIS and *in-situ* spectroradiometers. The different spatial resolution of the measurements and temporal differences between MERIS image acquisition and field data collection may have also contributed.

CHL-*a* and PC values derived from MERIS and *in-situ* spectroradiometry data from all the sites with Secchi disk values below 3 m in Table 2 are compared in Fig. 8. The real values of Lake Albufera are divided by 3 for visualization purposes. This comparison supports the usability of MERIS data and SCAPE-M processing for phytoplankton pigment retrieval over turbid waters. Correlation coefficients R^2 are 0.99 for both CHL-*a* and PC. The largest errors are found for low CHL-*a* and PC values, which cause the water reflectance to be relatively low at NIR wavelengths. This increases the impact of errors in atmospheric correction due to adjacency effects or a wrong aerosol model, as can also be observed from reflectance spectra plotted in Figs. 3 and 4 from Iznájar and Zurich sites. In this regard it must be considered that the PC algorithm was based on the optical properties of the eutrophic Lakes IJsselmeer and Loosdrecht (52.16°N, 5.0°E) (Simis et al., 2005), which limits its application to some of the sites in Fig. 8. On the other hand, the method was shown to be robust in a variety of geographically separated lakes (Ruiz-Verdú et al., 2008b). It must be stressed that the results in Fig. 7 are not intended to support the retrieval accuracy of the respective algorithms. Rather, these results show that the information that is needed to apply these or other

semiempirical band-ratio algorithms is retained in the MERIS reflectance data obtained with SCAPE-M.

CHL-*a* maps at IJsselmeer derived from MERIS images processed by SCAPE-M and the CHL-*a* algorithm are displayed in Fig. 9 together with red–green–blue (RGB) composites. Fig. 9 demonstrates the range in atmospheric and phytoplankton biomass distribution that was observed within Lake IJsselmeer between the two dates of image acquisition used in this study. On 3 August 2004 (Fig. 9(a), (b)), a hazy atmosphere with high jet contrails appears to be corrected in such a way that in the resulting map of CHL-*a* thick contrails were either masked out or do not appear to affect the CHL-*a* result. The image of 16 August 2005 (Fig. 9(c), (d)), displays widespread cirro-cumulus clouds around the lake, which itself was under a clear atmosphere, and severe phytoplankton blooms. The southwest section of the water body is Lake Markermeer, separated from Lake IJsselmeer by a dam. Lake Markermeer is characterized by lower phytoplankton biomass but higher loads of suspended sediments, as we can also make out from the CHL-*a* map.

4. Summary and Conclusions

A new approach to water reflectance retrieval from VNIR remote sensing data is validated in this work. SCAPE-M performs cloud screening, elevation and topographic correction, AOT550 and CWV retrieval, and reflectance retrieval sequentially from MERIS Level-1b data. Vegetation and bare soil pixels, as well as any dark surface, are used as a reference for the derivation of AOT550 maps over land and inland water pixels. Traditional approaches for AOT550 retrieval, like those based on neglecting water reflectance at NIR wavelengths or on the inversion of site-specific bio-optical models, are avoided by using land pixels in the vicinity of water targets as the basis for aerosol retrieval. The independence of surface reflectance retrievals of the reflectance spectral response is one of the advantages of this methodology for the retrieval of reflectance from continental water targets, although a site-specific bio-optical model may be employed later to derive water parameters from the SCAPE-derived reflectance. The inability to retrieve information on aerosol type and to correct for directional effects on water reflectance are identified deficiencies of SCAPE-M for the processing of MERIS data over water.

The performance of the SCAPE-M processor over inland water bodies has been tested by the direct comparison of MERIS-derived R_{rs} with *in-situ* data acquired during field campaigns at lakes and reservoirs all over Europe, with most of the sites being located at the Iberian Peninsula and subalpine regions. After the screening of cloud and sun-glint contamination cases, up to 20 match-ups between MERIS and ground acquisitions were available for reflectance intercomparison. Atmospheric measurements were also performed in 6 of them. AOT550 derived from MERIS data at Spanish validation sites showed a good correlation with CIMEL-based measurements taken at the sites. The correlation coefficient R^2 of 0.74 and the RMSE of 0.07 confirmed previous AOT550 validation exercises using AERONET data. The worst case for AOT550 was found at the Iznájar reservoir in the Southern Iberian Peninsula, where AOT retrieval is expected to fail due to the absence of green vegetation and dark pixels.

R_{rs} spectra derived by SCAPE-M from MERIS data showed a very good comparison with *in-situ* measurements at the nine Spanish sites where this validation was performed. It is believed that such good results over such a wide range of water conditions could not be obtained by retrieval approaches based on bio-optical models and multi-parameter inversions due to their strong site-specificity. Only in the case of the clear water Cuerda del Pozo reservoir a large reflectance error was found at NIR channels. This may be explained by poor compensation of adjacency effects, as a similar behavior was found in previous works in Maggiore and Garda lakes (Candiani et al., 2007; Giardino et al., 2008), or by a difference between the actual

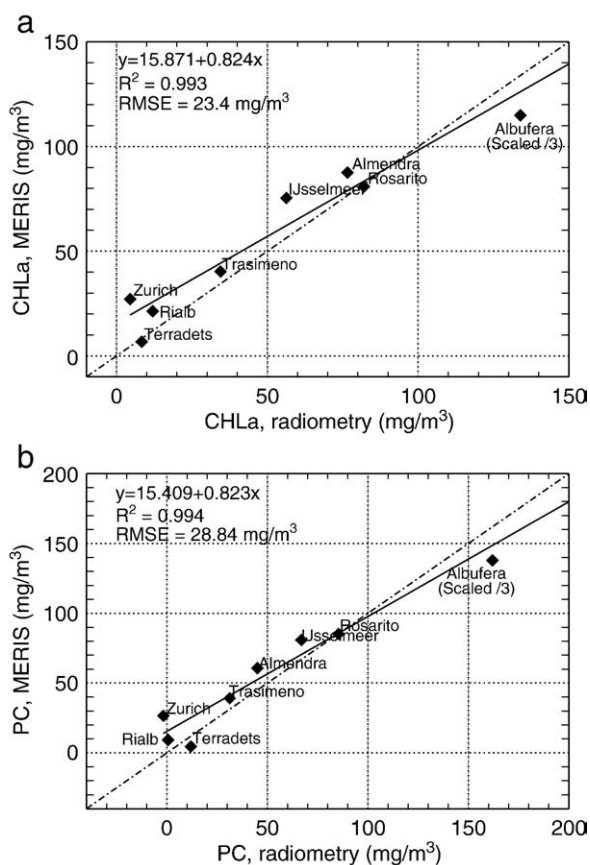


Fig. 8. Comparison between (a) CHL-*a* and (b) PC derived from SCAPE-M and *in-situ* reflectance data, for all study sites classified as "turbid waters". Values for Lake Albufera were scaled by 1/3 for better visualization.

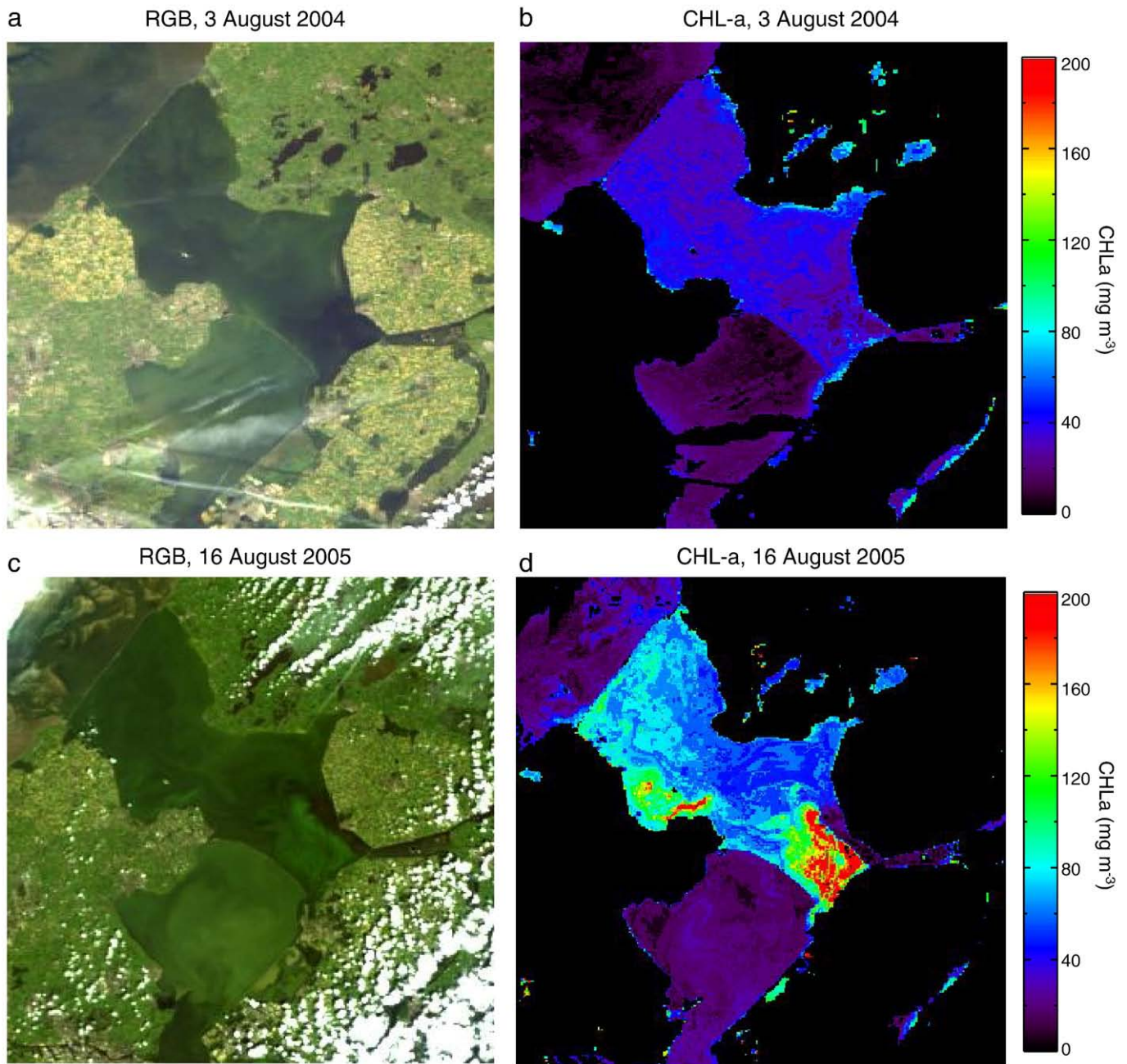


Fig. 9. True-color composites and CHL-*a* maps from SCAPE-M corrected MERIS images acquired over Lake IJsselmeer in August of 2004 and 2005.

aerosol type and the rural model assumed by SCAPE-M by default. A very good match between MERIS and ground-based reflectance spectra is also found in the turbid Trasimeno, Zurich and IJsselmeer lakes, but SCAPE-M is not able to provide realistic reflectance spectra, both in brightness and in spectral shapes, over the subalpine clear lakes Garda, Maggiore, Leman and Constance. MODTRAN4 based simulations at the Lake Constance acquisition configuration demonstrated that no combination of AOT550 and pure aerosol model (rural, urban or maritime) can provide reflectance spectra as those measured in the field. Residual adjacency effects, sun-glint contamination or even a bad parameterization of the aerosol vertical profile are considered possible error sources to explain the bad results of SCAPE-M over those sites.

SCAPE-M was also compared to the neural network-based BEAM lake processors designed for the retrieval of water composition from MERIS data. It was found that SCAPE-M performed better over turbid and semi-turbid waters, where the BEAM processors could not

reproduce some key spectral features of the reflectance spectra in the 500–750 nm window. This can be explained by the dependence of neural network-based algorithms on the training set applied to the derivation of the regression relationship; SCAPE-M, in turn, is not doing any *a-priori* assumption on the target spectral response, which enables its application to extreme water composition conditions. BEAM processors, however, provided better results over the darkest water bodies, possibly due to the compensation of errors in atmospheric characterization in the multi-parameter inversion.

Finally, a test of the ability of MERIS data to track water CHL-*a* and PC concentrations after SCAPE-M processing has also been performed as a part of the validation exercise. Semiempirical, band-ratio-based algorithms have been used to transfer from R_{rs} to CHL-*a* and PC concentrations, respectively. Results from data acquired over Lake IJsselmeer showed that MERIS data can reproduce to large extent the information provided by field radiometry in both CHL-*a* ($R^2 = 0.75$)

and PC ($R^2=0.83$), at least to the degree required for these band-ratio-based algorithms. Similar good correlations were found from the application of the CHL- α and PC algorithms to MERIS reflectance derived by SCAPE-M from all the turbid water validation sites.

The applicability of land-based atmospheric correction methods to inland and coastal waters, as an alternative to traditional models that make assumptions on the shape of the water reflectance or to those based on site-specific bio-optical models, is confirmed by the results presented in this work. The good performance of SCAPE-M over turbid waters, which are the most challenging ones in terms of atmospheric correction and the most important ones with respect to water quality monitoring, must be highlighted. However, the poor results in the retrieval of reflectance from clear waters are yet to be solved. The formulation of different aerosol models and enhanced adjacency and sun-glint corrections are suggested to improve the SCAPE-M atmospheric processor.

Acknowledgments

SCAPE-M was developed by LG under the support of a PhD fellowship from the Spanish Ministry of Education and Science and the project *Development of algorithms for the exploitation of MERIS data over land* (ESRIN/Contract No 16545/02/I-LG). MERIS data of Italian lakes were made available through the ESA AO-553 MELINOS project. We are very grateful to M. Bresciani from CNR-IREA for data processing and to M. Musanti for his assistance in the field. This work would not be possible without contributions provided by CRA-Sirmione, CNR-ISE and ARPA Umbria in lakes Garda, Maggiore and Trasimeno, respectively. Data collection at Lake IJsselmeer was made possible through grant EO-053 from the User Support Programme managed by the programme office External Research of the Netherlands Organization for Scientific Research-National Institute for Space Research (NWO-SRON). M. Jehle and O. Frey from RSL are thanked for enabling the Lake Zurich field measurements with their private yacht and UMR CARTEL Thonon-Les-Bains for providing staff and a vessel for the Lake Geneva field campaign. We further acknowledge the useful comments of four anonymous reviewers that helped to improve the manuscript. The SCAPE-M code is available on request from the authors.

References

- Bailey, S. W., & Werdell, P. J. (2006). A multi-sensor approach for the on-orbit validation of ocean color satellite data products. *Remote Sensing of Environment*, 102, 12–23.
- Béal, D., Baret, F., Bacour, C., & Gu, X. -F. (2007). A method for aerosol correction from the spectral variation in the visible and near infrared: Application to the MERIS sensor. *International Journal of Remote Sensing*, 28, 761–779.
- Berk, A., Anderson, G. P., Acharya, P. K., Hoke, M. L., Chetwynd, J. H., Bernstein, L. S., Shettle, E. P., Matthew, M. W., Adler-Golden, S. M., 2003. MODTRAN4 version 3 revision 1 user's manual. Tech. rep., Air Force Research Laboratory, Hanscom Air Force Base, MA, USA.
- Candiani, G., Giardino, C., & Brando, V. E. (2007, July). Adjacency effects and bio-optical model regionalisation: MERIS data to assess lake water quality in the Subalpine ecoregion. In ESA/ESRIN (Ed.), *Proceedings of the ENVISAT Symposium*. Montreux, Switzerland.
- Dekker, A. G., Hoogenboom, H. J., Goddijn, L. M., & Malthus, T. J. (1997). The relation between inherent optical properties and reflectance spectra in turbid inland waters. *Remote Sensing Reviews*, 15, 59–74.
- Doerffer, R., Schiller, H., May 2008. MERIS regional coastal and lake case 2 water project atmospheric correction ATBD. Tech. rep., GKSS Research Center 21502 Geesthacht.
- Duforêt, L., Froin, R., & Dubuisson, P. (2007). Importance and estimation of aerosol vertical structure in satellite ocean-color remote sensing. *Applied Optics*, 46, 1107–1118.
- Floriciou, D., & Rott, H. (2005, September). Atmospheric correction of MERIS data over perialpine regions. In ESA/ESRIN (Ed.), *Proceedings of the MERIS-(A)ATSR workshop*. Frascati, Italy.
- Fomferra, N., & Brockmann, C. (2005, September). Beam—The ENVISAT MERIS and AATSR toolbox. In ESA/ESRIN (Ed.), *Proceedings of the MERIS-(A)ATSR workshop*. Frascati, Italy. URL <http://www.brockmann-consult.de/beam/>
- Gao, B. -C., Montes, M. J., Li, R. -R., Dierssen, H. M., & Davis, C. O. (2007). An atmospheric correction algorithm for remote sensing of bright coastal waters using MODIS land and ocean channels in the solar spectral region. *IEEE Transactions on Geoscience and Remote Sensing*, 45, 1835–1843.
- Giardino, C., Brando, V. E., Dekker, A. G., Strömbeck, N., & Candiani, G. (2007). Assessment of water quality in Lake Garda (Italy) using Hyperion. *Remote Sensing of Environment*, 109, 183–195.
- Giardino, C., Bresciani, M., Brando, V. E., & Dekker, A. G. (2008, September). Observations of the largest Italian lakes from MERIS. In ESA/ESRIN (Ed.), *Proceedings of the 2nd MERIS/(A)ATSR user workshop*. Frascati, Italy.
- Gitelson, A. A., Dall'Omo, G., Moses, W., Rundquist, D. C., Barrow, T., Fisher, T. R., Gurlin, D., & Holz, J. (2008). A simple semi-analytical model for remote estimation of chlorophyll- α in turbid waters: Validation. *Remote Sensing of Environment*, 112, 3582–3593.
- Gitelson, A. A., Schalles, J. F., & Hladik, C. M. (2007). Remote chlorophyll- α retrieval in turbid, productive estuaries: Chesapeake Bay case study. *Remote Sensing of Environment*, 109, 464–472.
- Gons, H. J. (1999). Optical teledetection of chlorophyll α in turbid inland waters. *Environmental Science & Technology*, 33, 1127–1132.
- Gons, H. J., Rijkeboer, M., & Ruddick, K. G. (2005). Effect of a waveband shift on chlorophyll retrieval from MERIS imagery of inland and coastal waters. *Journal of Plankton Research*, 27(1), 125–127.
- Gordon, H. R. (1997). Atmospheric correction of ocean color imagery in the Earth Observing System era. *Journal of Geophysical Research*, 102, 17081–17105.
- Gordon, H. R., & Wang, M. (1978). Removal of atmospheric effects from satellite imagery of the oceans. *Applied Optics*, 17, 1631–1636.
- Gordon, H. R., & Wang, M. (1994). Retrieval of water-leaving radiance and aerosol optical thickness over the oceans with SeaWiFS: A preliminary algorithm. *Applied Optics*, 33, 443–452.
- Guanter, L., Gómez-Chova, L., & Moreno, J. (2008). Coupled retrieval of aerosol optical thickness, columnar water vapor and surface reflectance maps from ENVISAT/MERIS data over land. *Remote Sensing of Environment*, 112, 2898–2913.
- Guanter, L., González-Sampedro, M. C., & Moreno, J. (2007). A method for the atmospheric correction of ENVISAT/MERIS data over land targets. *International Journal of Remote Sensing*, 28, 709–728.
- Holben, B. N., Eck, T. F., Slutsker, I., Tanre, D., Buis, J. P., Setzer, A., Vermote, E., Reagan, J. A., Kaufman, Y., Nakajima, T., Lavenue, F., Jankowiak, I., & Smirnov, A. (1998). AERONET—A federated instrument network and data archive for aerosol characterization. *Remote Sensing of Environment*, 66, 1–16.
- Hovis, W. A., Clark, D. K., Anderson, F., Austin, R. W., Wilson, W. H., Baker, E. T., Ball, D., Gordon, H., Mueller, J. L., El-Sayed, S., Sturm, B., Wrigley, R. C., & Yentsch, C. (1980). Nimbus-7 coastal zone color scanner: System description and initial imagery. *Nature*, 210, 60–63.
- Kratzer, S., Brockmann, C., & Moore, G. (2008). Using MERIS full resolution data to monitor coastal waters—A case study from Himmerfjärden, a fjord-like bay in the northwestern Baltic Sea. *Remote Sensing of Environment*, 112, 2284–2300.
- Kuchinke, C. P., Gordon, H. R., & Franz, B. A. (2009). Spectral optimization for constituent retrieval in case 2 waters I: Implementation and performance. *Remote Sensing of Environment*, 113, 571–587.
- Lavender, S. J., Pinkerton, M. H., Moore, G., Aiken, J., & Blondeau-Patissier, D. (2005). Modification to the atmospheric correction of SeaWiFS ocean colour images over turbid waters. *Continental Shelf Research*, 25, 539–555.
- McClain, C. R., Feldman, G. C., & Hooker, S. B. (2004, January–February). An overview of the SeaWiFS project and strategies for producing a climate research quality global ocean bio-optical time series. *Deep Sea Research Part II. Topical Studies in Oceanography*, 51, 5–42.
- Moore, G. F., Aiken, J., & Lavender, S. J. (1999). The atmospheric correction of water colour and the quantitative retrieval of suspended particulate matter in case II waters: Application to MERIS. *International Journal of Remote Sensing*, 20, 1713–1733.
- Morel, A., & Bélanger, S. (2006). Improved detection of turbid waters from ocean color sensors information. *Remote Sensing of Environment*, 102, 237–249.
- Odermatt, D., Heege, T., Nieke, J., Kneubühler, M., & Itten, K. (2008). Water quality monitoring for Lake Constance with a physically based algorithm for MERIS data. *Sensors*, 8, 4582–4589.
- Odermatt, D., Kiselev, V., Heege, T., Kneubühler, M., & Itten, K. I. (2008, September). Adjacency effect considerations and air/water constituent retrieval for Lake Constance. In ESA/ESRIN (Ed.), *Proceedings of the 2nd MERIS/(A)ATSR user workshop*. Frascati, Italy.
- Park, Y. -J., & Ruddick, K. (2005). Model of remote-sensing reflectance including bidirectional effects for case 1 and case 2 waters. *Applied Optics*, 44, 1236–1249.
- Ramon, D., & Santer, R. (2005, September). Aerosol over land with MERIS, present and future. In ESA/ESRIN (Ed.), *Proceedings of the MERIS-(A)ATSR workshop*. Frascati, Italy.
- Rast, M., Bézy, J. L., & Bruzzi, S. (1999). The ESA Medium Resolution Imaging Spectrometer MERIS—A review of the instrument and its mission. *International Journal of Remote Sensing*, 20, 1681–1702.
- Ruddick, K. G., Ovidio, F., & Rijkeboer, M. (2000). Atmospheric correction of SeaWiFS imagery for turbid coastal and inland waters. *Applied Optics*, 39, 897–912.
- Ruiz-Verdú, A., Koponen, S., Heege, T., Doerffer, R., Brockmann, C., Kallio, K., Pyhälähti, T., Peña-Martínez, R., Polvorinos, Á., Heblinski, J., Ylöstalo, P., Conde, L., Odermatt, D., Estellés, V., & Pulliainen, J. (2008, September). Development of MERIS lake water algorithms: Validation results from Europe. In ESA/ESRIN (Ed.), *Proceedings of the 2nd MERIS/(A)ATSR user workshop*. Frascati, Italy.
- Ruiz-Verdú, A., Simis, S. G. H., De Hoyos, C., Gons, H. J., & Peña-Martínez, R. (2008). An evaluation of algorithms for the remote sensing of cyanobacterial biomass. *Remote Sensing of Environment*, 112, 4–16.
- Salomonson, V. V., Barnes, W. L., Maymon, P., Montgomery, H., & Ostrow, H. (1989). MODIS: Advanced facility instrument for studies of the Earth as a system. *IEEE Transactions on Geoscience and Remote Sensing*, 27, 145–153.
- Santer, R., Vidot, J., & Aznay, O. (2005, September). Standard aerosol model families used for atmospheric correction: How comparable are they? How validate are they? In ESA/ESRIN (Ed.), *Proceedings of the MERIS-(A)ATSR workshop*. Frascati, Italy.

- Santer, R., Zagolski, F., Gilson, M., January 2009. Improved Contrast between Ocean and Land (ICOL) algorithm theoretical basis document. Tech. rep., ULCO, Wimereux, France.
- Schiller, H., & Doerffer, R. (2005). Improved determination of coastal water constituent concentrations from MERIS data. *IEEE Transactions on Geoscience and Remote Sensing*, 43, 1585–1591.
- Schroeder, T., Behnert, I., Schaale, M., Fischer, J., & Doerffer, R. (2007). Atmospheric correction algorithm for MERIS above case-2 waters. *International Journal of Remote Sensing*, 28, 1469–1486.
- Siegel, D., Wang, M., Maritorena, S., & Robinson, W. (2000). Atmospheric correction of satellite ocean color imagery: The black pixel assumption. *Applied Optics*, 39, 3582–3591.
- Simis, S. G. H., Peters, S. W. M., & Gons, H. J. (2005). Remote sensing of the cyanobacterial pigment phycocyanin in turbid inland water. *Limnology and Oceanography*, 50, 237–245.
- Simis, S. G. H., Ruiz-Verdú, A., Domínguez-Gómez, J. A., Peña-Martínez, R., Peters, S. W. M., & Gons, H. J. (2007). Influence of phytoplankton pigment composition on remote sensing of cyanobacterial biomass. *Remote Sensing of Environment*, 106, 414–427.
- Thuillier, G., Herse, M., Labs, D., Foujols, T., Peetermans, M., Gillotay, D., Simon, P. C., & Mandel, H. (2003). The solar spectral irradiance from 200 to 2400 nm as measured by the SOLSPEC spectrometer from the Atlas and Eureka missions. *Solar Physics*, 214, 1–22.
- Vermote, E. F., El-Saleous, N., Justice, C. O., Kaufman, Y. J., Privette, J. L., Remer, L., Roger, J. C., & Tanré, D. (1997). Atmospheric correction of visible to middle infrared EOS-MODIS data over land surface: Background, operational algorithm and validation. *Journal of Geophysical Research*, 102, 17131–17141.
- Vidot, J., & Santer, R. (2005). Atmospheric correction for inland waters—Application to SeaWiFS. *International Journal of Remote Sensing*, 26, 3663–3682.
- Viollier, M., Tanré, D., & Deschamps, P. Y. (1980). An algorithm for remote sensing of water color from space. *Boundary-Layer Meteorology*, 18, 247–267.
- Wang, M. (2007). Remote sensing of the ocean contributions from ultraviolet to near-infrared using the shortwave infrared bands: Simulations. *Applied Optics*, 46, 1535–1547.