

Comparison of iCOR and Rayleigh atmospheric correction methods on Sentinel-3/OLCI images for a shallow eutrophic reservoir (#74477)

1

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Comparison of iCOR and Rayleigh atmospheric correction methods on Sentinel-3/OLCI images for a shallow eutrophic reservoir

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Remote sensing of inland waters is challenging, but also important, due to the need to monitor the ever-increasing harmful algal blooms (HABs), which have serious effects on water quality. The Ocean and Land Color Instrument (OLCI) of the Sentinel-3 satellites program is capable of providing images for the monitoring of such waters. Atmospheric correction is a necessary process in order to retrieve the desired surface-leaving radiance signal and several atmospheric correction methods have been developed through the years. In this study, we evaluated the possible differences between a partial atmospheric correction method accounting for Rayleigh scattering and a full atmospheric correction method (iCOR), applied on Sentinel-3/OLCI images of a shallow, highly eutrophic water reservoir. For the complete evaluation of the two methods, in addition to the comparison of the band values, chlorophyll (CHL) and cyanobacteria (CI) indices were also calculated and their values were intercompared. The results showed, that although the absolute values between the two correction methods did not coincide, there was a very good correlation between the bands and the CHL and CI indices values. Therefore, since iCOR correction image processing time is 25 times longer than Rayleigh correction, it seems that the Rayleigh partial correction method may be sufficient for seasonal water monitoring, especially in cases of long time-series, enhancing time and resources use efficiency.

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Abstract

Remote sensing of inland waters is challenging, but also important, due to the need to monitor the ever-increasing harmful algal blooms (HABs), which have serious effects on water quality. The Ocean and Land Color Instrument (OLCI) of the Sentinel-3 satellites program is capable of providing images for the monitoring of such waters. Atmospheric correction is a necessary process in order to retrieve the desired surface-leaving radiance signal and several atmospheric correction methods have been developed through the years. In this study, we evaluated the possible differences between a partial atmospheric correction method accounting for Rayleigh scattering and a full atmospheric correction method (iCOR), applied on Sentinel-3/OLCI images of a shallow, highly eutrophic water reservoir. For the complete evaluation of the two methods, in addition to the comparison of the band values, chlorophyll (CHL) and cyanobacteria (CI) indices were also calculated and their values were intercompared. The results showed, that although the absolute values between the two correction methods did not coincide, there was a very good correlation between the bands and the CHL and CI indices values. Therefore, since iCOR correction image processing time is 25 times longer than Rayleigh correction, it seems that the Rayleigh partial correction method may be sufficient for seasonal water monitoring, especially in cases of long time-series, enhancing time and resources use efficiency.

Introduction

Harmful algal blooms (HABs)

Recurrent blooms of harmful algae and cyanobacteria (HABs) in coastal and inland water systems are a major concern for environmental and public health authorities worldwide. They are associated with eutrophication and in particular with phosphorus and nitrogen loading due to runoff from rural areas (Anderson et al., 2008; Heisler et al., 2008; Mazard et al., 2016; O'Neil et al., 2012) and also with climate change and CO₂ concentration and temperature increase (Glibert, 2020; Gobler, 2020; Griffith and Gobler, 2020; O'Neil et al., 2012; Raven et al., 2020). Other factors are high pH and light (Bartosh and Banks, 2006; Ni et al., 2012).

The effects of these blooms may concern changes in taste and smell of water supply sources, development of a thick crust on the surface of the lake and lack of water purity (Chorus and Bartram, 1999). Additionally, from a biological perspective, possible toxic effects on other algae, invertebrates and fish and anoxic conditions that alter the structure of benthic macro-invertebrates may appear (Havens, 2008). Finally, the toxic secondary metabolites produced by blue-green algae may cause serious health problems in mammals and wildlife, because they affect the endocrine, dermal and nervous systems (Carmichael, 2001).

Sentinel-3/OLCI

The advancements in satellite remote sensing during the last decades has led to its significant contribution in numerous environmental applications. The Sentinel-3 satellites are a mission organized by the European Space Agency (ESA) and the European Meteorological Satellite Exploitation Agency (EUMETSTAT) under the Copernicus program, formerly known as the Global Monitoring for Environment and Security (GMES). The Sentinel-3 mission comprises two similar satellites A and B, with launch dates February 16, 2016 and April 25, 2018 respectively. Both satellites are solar-synchronous with a polar orbit, operating at an average altitude of 815 km and with an inclination of 98.6° (Yang et al., 2019). Among others, they carry an Ocean and Land Color Instrument (OLCI) which covers a spectral range from 400 to 1020 nm (21 spectral bands), with 300 m spatial resolution and approximately daily revisit cycle.

Ocean Color images have been available since 1978 thanks to the Coastal Zone Color Scanner (CZCS) mission. From 2002 to 2012, the Medium Resolution Imaging Spectrometer (MERIS) on ESA's ENVISAT platform provided unprecedented monitoring capability for coastal and inland water systems (Kravitz et al., 2020). The OLCI Instrument onboard the Sentinel-3 satellites is based on the mechanical and imaging design of ENVISAT MERIS and may be considered as MERIS heritage for ocean and land color monitoring. It includes six more spectral bands than MERIS (21 to 15), which are centered at 400 and 674 nm (water constituents retrieval improvement), 761, 764, and 768 nm (O₂ gas absorption correction improvements), and 1020 nm (atmospheric correction improvement) (Mograne et al., 2019).

Atmospheric correction

Satellite sensors measure the top-of-atmosphere (TOA) signal from the surface-atmosphere system in visible and near-infrared parts of the spectrum. The atmospheric path radiance received by a sensor at the TOA can be mainly decomposed into Rayleigh and aerosol scattering (Feng et al., 2018), with the Rayleigh-scattering radiance being the most dominant component of the TOA signal (Shanmugam et al., 2019). The process of removing the atmospheric path signal from the TOA signal in order to retrieve the desired surface-leaving radiance signal is referred to as atmospheric correction (Gordon, 1997). It is worth noting, that after five years of Sentinel-3 operation, ESA is still providing only limited atmospherically corrected (Level 2) data. So, for acquiring information about the environment (for example monitoring of cyanobacterial blooms) from the satellite images, atmospheric correction is necessary and several atmospheric correction algorithms have been developed through the years.

iCOR & Rayleigh atmospheric correction methods

iCOR is a free open-source atmospheric correction software (Ibrahim et al., 2018; Nurgiantoro et al., 2019) that can be used as an ESA Sentinel Application Platform (SNAP) plug-in for processing Landsat-8/OLI, Sentinel-2/MSI and Sentinel-3/OLCI images. iCOR runs without user interaction, derives the required input parameters from the image and is designed to be applicable to inland waters, coastal waters and land.

The iCOR workflow includes four steps (~~“Atmospheric correction software for Sentinel-3 Vito remote sensing,”~~ n.d.; König et al., 2019; Stefan et al., 2018): (1) classification of land/water pixels (2) AOT retrieval over land following the approach of (Guanter et al., 2007) and extension to black water pixels in the Short Wave InfraRed (SWIR) (3) adjacency correction and (4) atmospheric correction using pre-calculated MODTRAN 5 Look Up Tables based on a rural aerosol model (De Keukelaere et al., 2018). Above water the SIMilarity Environment Correction (SIMEC) is used, which is based on the correspondence with the Near InfraRed (NIR) similarity spectrum and is described in (Sterckx et al., 2015, 2011). Above land, fixed background ranges are used.

A Rayleigh atmospheric correction algorithm, was originally designed for MERIS, is included in SNAP software. The current version of SNAP software also supports OLCI and Sentinel-2 MSI instruments. Specifically, Rayleigh correction can be applied to: MERIS bands 1 to 15 (N1 format or MERIS 4th reprocessing format), Sentinel-3 OLCI L1B bands 1-21 and Sentinel-2 MultiSpectral Instrument (MSI) L1C bands 1 to 9. The Rayleigh correction processor as its described in S3TBX - Rayleigh Correction Tutorial (2021) (Ruescas and Müller, n.d.) has five different outputs: Rayleigh optical thickness (ROT), Bottom of Rayleigh Reflectance (BRR), gaseous corrected TOA reflectance, TOA reflectance bands and air mass ~~(the air mass term is written to the target product, otherwise is set to False).~~

Aim of the study

The aim of this study is to evaluate the possible differences between a partial atmospheric correction method accounting for Rayleigh scattering and a full atmospheric correction method

(iCOR), applied on Sentinel-3/OLCI images for the study of shallow eutrophic lakes. Even though a full atmospheric correction method **may be obviously considered better** compared to Rayleigh correction, possible large differences in processing time between the two methods, may be especially critical in cases of studies involving large time-series datasets.

Materials and Methods

Study site

The study area is the Karla Reservoir, Thessaly, Greece (39°29'27"N 22°49'19"E) that has maximum water depth of 4.5 - 5 m and the maximum allowable water volume of the reservoir can reach $200 \times 10^6 \text{ m}^3$, but only half can be extracted. Some important environmental problems of the Karla Reservoir are the eutrophication and the very frequent and prolonged cyanobacterial blooms that produce toxins (Gkelis et al., 2017; Oikonomou et al., 2012) as well as the high mortality and quite large amounts of microcystins in the reservoir's major fish species (Papadimitriou et al., 2013) but also migrating birds (Papadimitriou et al., 2018).

Satellite images

The satellite images, which were used in this study, were downloaded from the Copernicus Open Access Hub (<https://scihub.copernicus.eu/>), which provides full and free access to images of the Sentinel-1, Sentinel-2, Sentinel-3 and Sentinel-5P satellites. 53 cloud free, full resolution (300 m pixel size) Level-1B Sentinel-3/OLCI images (OL_1__EFR__ products), providing radiometrically calibrated, ortho-geolocated and spatially re-gridded Top Of Atmosphere (TOA) radiances, were used.

Atmospheric correction application

Data from all images were converted from TOA radiances to Bottom Of Atmosphere (BOA) reflectance using both a partial atmospheric correction method accounting for Rayleigh scattering and a full atmospheric correction method (iCOR) and the results obtained with the two methods were intercompared. Image processing was performed with SNAP - ESA Sentinel Application Platform v8.0 (<http://step.esa.int>), which includes a Rayleigh correction algorithm, while iCOR is available as a SNAP plugin. Rayleigh correction is a straightforward procedure in SNAP, completing rather fast, i.e. in approximately 5 min for a Sentinel-3 image. On the other hand, for the iCOR correction, several options have to be selected by the user and the procedure is rather time-consuming, taking about 2 hours to be completed in a personal computer with a 7th Generation Intel® Core™ i5 4 core / 4 threads processor and 16 GB of RAM. In this study, for the iCOR correction the Atmospheric Optical Transmittance (AOT), water vapor and ozone concentrations were estimated from the corresponding data included in the Sentinel-3 images *per ce*.

From the 21 spectral bands (400 – 1020 nm) that exist in the Level 2B Sentinel-3 images and the Rayleigh corrected ones, 16 bands are included in the iCOR corrected images, since bands

13 (761.25 nm), 14 (764.375 nm), 15 (767.5 nm), 19 (900 nm) and 20 (940 nm) are used during the correction processing (Figure 1). Accordingly, band intercomparison between Rayleigh and iCOR corrected images was performed for the bands common in both processes.

From all atmospherically corrected images with both methods data were extracted for 49 pixels (7x7 rectangle) located approximately in the center of the Karla Reservoir (Figure 2).

Indices calculation

One of the most common problems in lake monitoring through remote sensing techniques is the phytoplankton abundance. Accordingly, to further evaluate the above-described correction methods, two indices, i.e. for chlorophyll (CHL) and phycocyanin (CI), were calculated from the atmospherically corrected spectral data from both methods, according to the following formulas, which provide accurate estimations in eutrophic waters (Gitelson et al., 2008; Wynne et al., 2008):

- $CHL = \left(\frac{1}{r_{665}} - \frac{1}{r_{708}} \right) \times r_{753}$
- $CI = - (r_{681} - r_{665} - (r_{708} - r_{665}) \times (\lambda_{681} - \lambda_{665}) / (\lambda_{708} - \lambda_{665}))$

where r is the spectral reflectance at the indicated wavelength and λ is the wavelength.

Statistics

For the comparison of the two correction methods a correlation analysis was performed using the JASP v. 0.14 software (JASP Team (2021). JASP (v. 0.14) [Windows 10] and the Pearson's correlation coefficient (r), significance level (P) and intercept and slopes of their linear relationships are given. Comparisons were made for all 53 images both at pixel level and at pixel average level for each image/date (49 pixels per image). Correlations for each band common between the two correction methods (16 bands) and for chlorophyll (CHL) and phycocyanin (CI) indices were performed.

Results

Band comparison

Band intercomparison revealed good correlations both at pixel level and pixel average level (Table 1), with correlation coefficients higher than 0.7. Especially for the bands used in chlorophyll and phycocyanin indices calculation, correlation coefficients higher than 0.8 were obtained (Figure 3). As expected, for all bands Rayleigh corrected data show higher values compared to iCOR, since the former method concerns a partial atmospheric correction. However, the differences between the two methods are rather small, confirming that the Rayleigh correction accounts for the most dominant component of the TOA signal (Shanmugam et al., 2019).

Indices comparison

High correlation patterns were also found for the chlorophyll and cyanobacteria indices, with the later performing slightly better (Figures 4 and 5). As in the case of band intercomparison,

there are differences in the indices absolute values between the two methods, with the Rayleigh underestimating both indices, especially at high range values.

Discussion

iCOR has been systematically evaluated in comparison with several other full atmospheric correction methods (Acolite, C2RCC, l2gen, Polymer, Sen2Cor, ATCOR) for land images of Sentinel-2 and Sentinel-3/OLCI (Rumora et al., 2020; Wolters et al., 2021), for inland water images of Sentinel-2 MSI and Sentinel-3/OLCI (Kravitz et al., 2020; Pahlevan et al., 2021; Pereira-Sandoval et al., 2019; Renosh et al., 2020; Warren et al., 2019), even in arctic sea ice images of Sentinel-2 MSI (König et al., 2019). Overall, it gives good results and is a reliable method for inland water images atmospheric correction.

The comparison of the two atmospheric correction methods in this study revealed very good correlations for all bands and indices (CHL and CI). Considering these results, it appears that for Sentinel-3/OLCI images in a shallow eutrophic reservoir such as Karla Reservoir, both methods can be used to calculate the CHL and CI indices with similar success. Therefore, one can use either of the two atmospheric corrections for the seasonal monitoring of the reservoir, without though the absolute values coinciding between the two methods. Practically, since iCOR correction is much more demanding and needs much more computational power and time to process an image, it seems that the partial correction of the Rayleigh method is sufficient, with obvious benefits in time and resource use efficiency, especially in cases of long time-series data.

Similar results have been reported by Matthews et al. (2012), examining an algorithm for the calculation of chlorophyll-a in MERIS inland water images and stating that for broad trophic status assessment, simple Rayleigh atmospheric corrections are likely sufficient and avoid the more complicated and error-prone aerosol atmospheric corrections in turbid case II waters (waters which cannot be described by only one optical constituent of the water column). To the best of our knowledge, there has been no other research comparing a complete atmospheric correction with a partial atmospheric correction for Rayleigh scattering in a shallow eutrophic reservoir.

Conclusions

In conclusion, even though it is not recommended to replace the full atmospheric correction algorithms, the application of only a partial correction for Rayleigh scattering in a shallow eutrophic reservoir seems sufficiently functional, with obvious advantages from time and resource use perspective. The 25 times faster and/or less resource demanding image processing of the Rayleigh correction method compared to iCOR may be of critical importance, especially in cases of long timeseries for monitoring algal blooms and water quality characteristics in shallow reservoirs. Additional research is needed to confirm our results in other shallow eutrophic lakes and probably examine and extend the applicability of the Rayleigh correction in general. To that purpose, comparisons with *in-situ* data for a full assessment of the prospects of applying only a partial atmospheric correction for Rayleigh scattering should be addressed.

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Table 1(on next page)

Band intercomparison statistics (intercept, slope and correlation coefficient r) between iCOR and Rayleigh corrected data.

For all bands $P < 0.0001$ and $N = 2597$.

Band	Wavelength, nm	Intercept	Slope	r
1	400	0.0410	0.6559	0.734
2	412.5	0.0431	0.6759	0.762
3	442.5	0.0379	0.6881	0.760
4	490	0.0326	0.7553	0.807
5	510	0.0288	0.8094	0.849
6	560	0.0162	0.9057	0.933
7	620	0.0180	0.8620	0.904
8	665	0.0194	0.8882	0.910
9	673.75	0.0199	0.8809	0.896
10	681.25	0.0198	0.8809	0.896
11	708.75	0.0170	0.8586	0.972
12	753.75	0.0172	0.9272	0.947
16	778.75	0.0162	0.9284	0.951
17	865	0.0144	0.9191	0.945
18	885	0.0140	0.9092	0.944
21	1020	0.0114	0.9122	0.952

Figure 1

Band data from the original Level-1B image (Radiance) and the corresponding Rayleigh and iCOR corrected images (Reflectance) for 16/09/2017.

Data are average $\pm$ SD from 49 pixels.

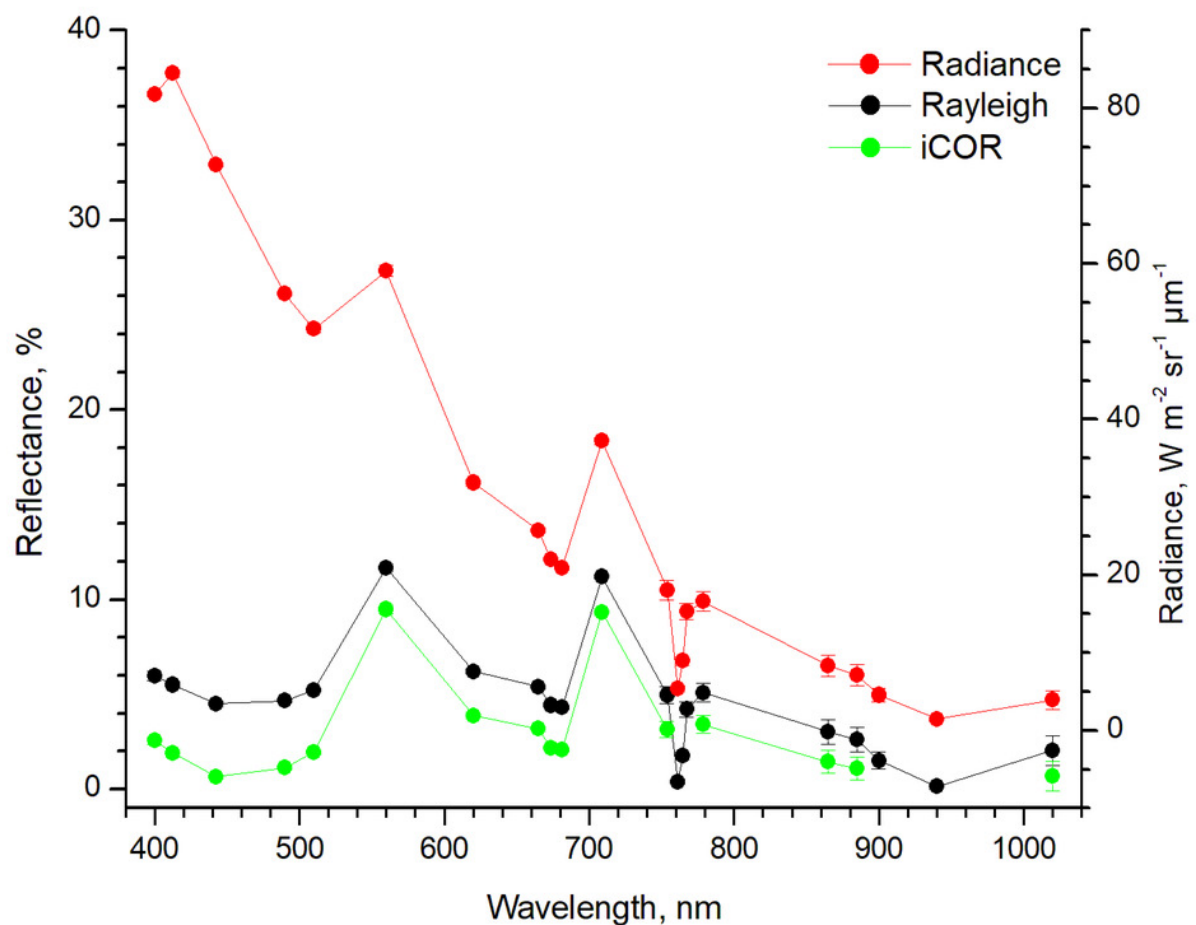


Figure 2

The Karla Reservoir with the centres of the 49 pixels used in the study indicated with red dots.

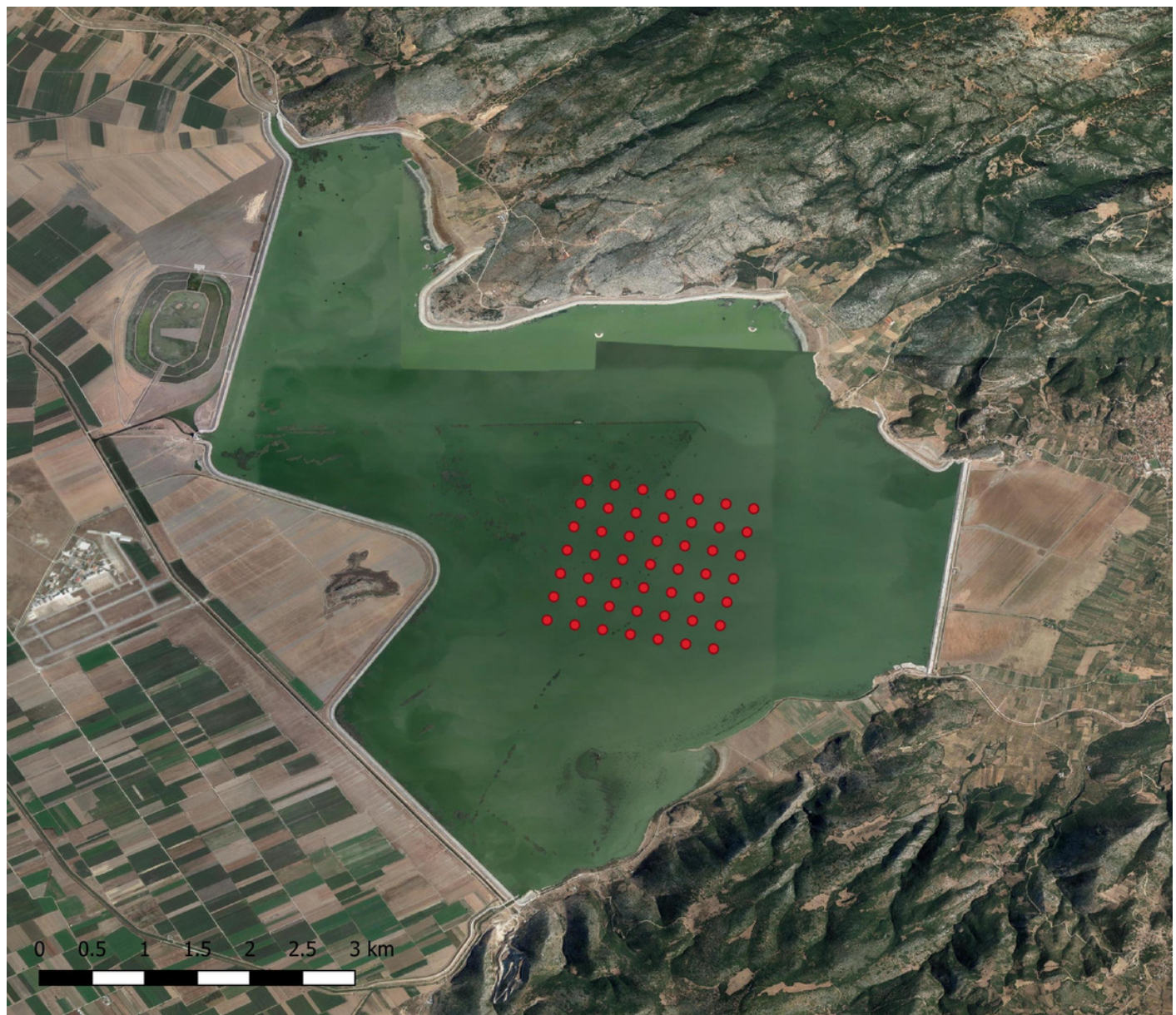


Figure 3

Correlations between the bands used in the calculation of chlorophyll and cyanobacteria indices.

For all bands $P < 0.0001$ and $N = 2597$.

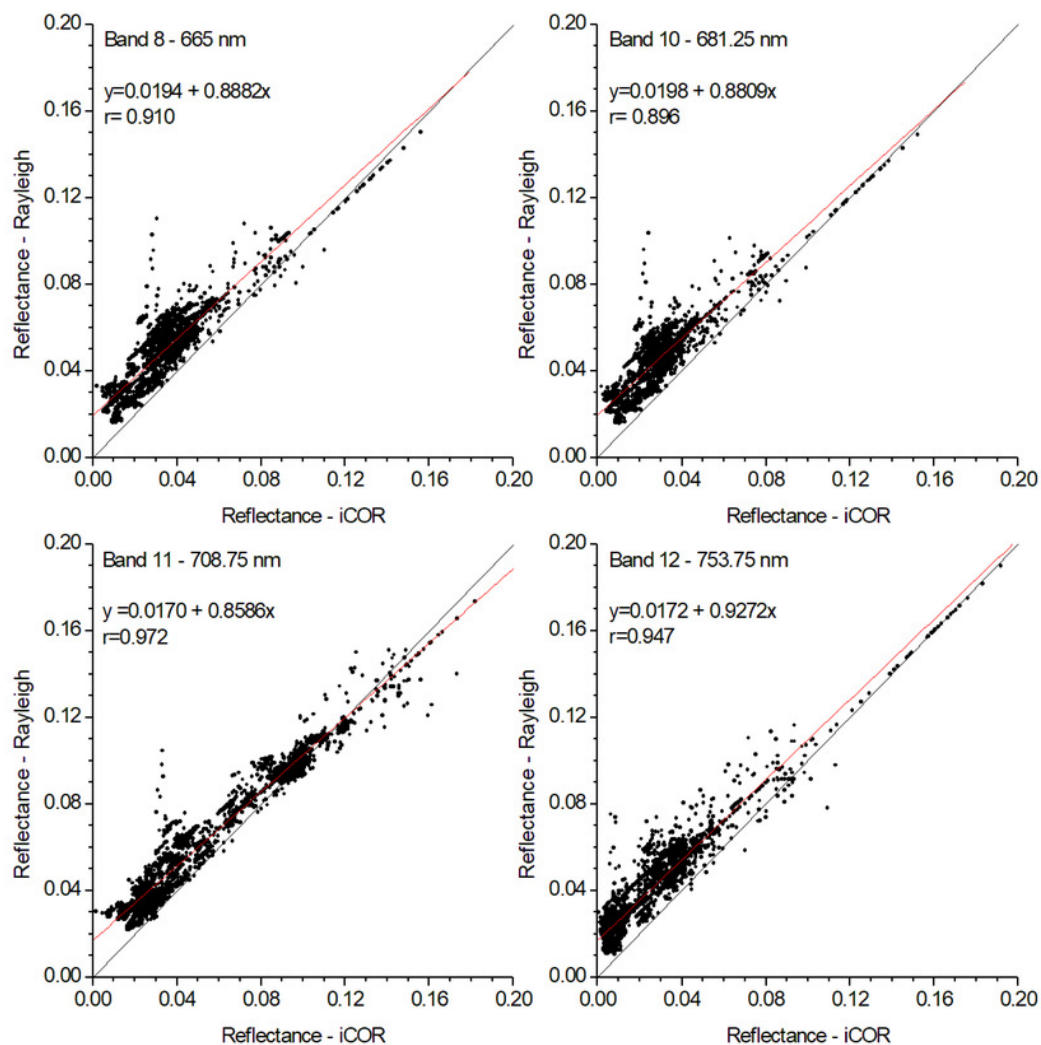


Figure 4

Correlations between iCOR and Rayleigh corrected data for chlorophyll and cyanobacteria indices at pixel level (2597 pixels).

For both indices $P < 0.0001$ and $N = 2597$.

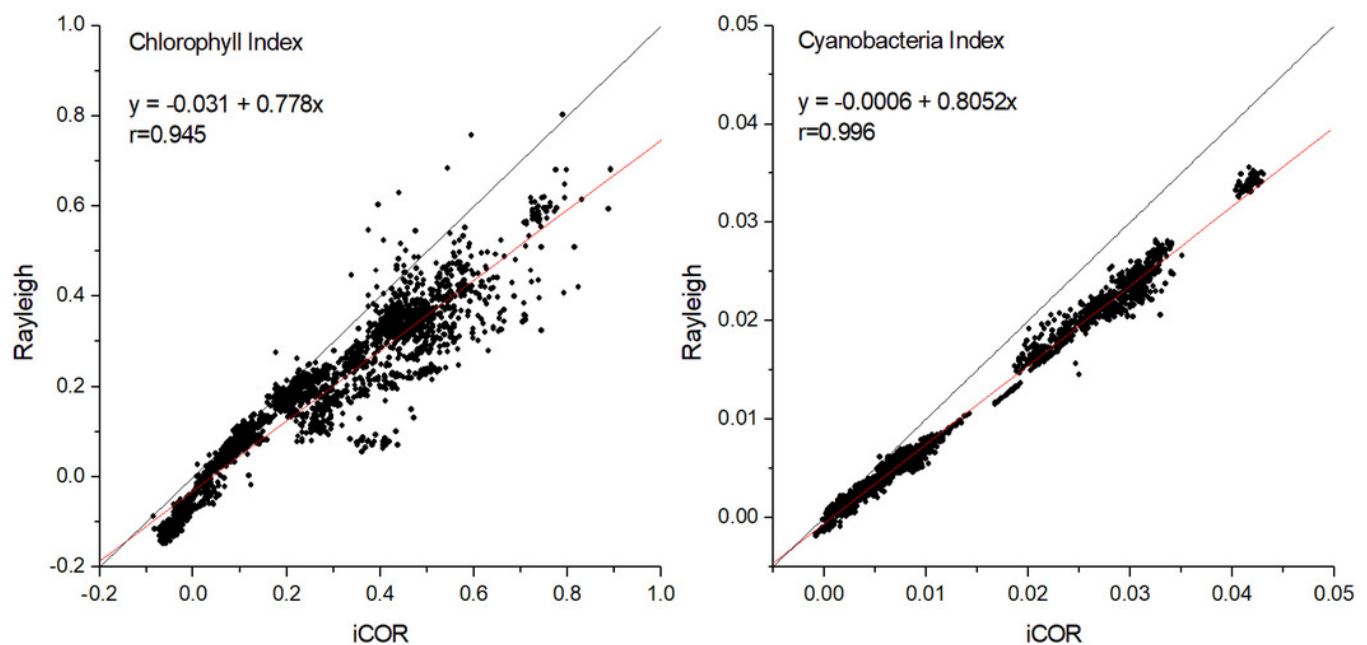


Figure 5

Correlations between iCOR and Rayleigh corrected data for chlorophyll and cyanobacteria indices at pixel average level (53 dates).

For both indices $P < 0.0001$ and $N = 53$.

