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# Evaluating the Applicability of Ocean Color Algorithms in the Fiji Region From In Situ Bio-Optical Data

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## ABSTRACT

Tropical islands 's oceanic biogeochemical environments may be influenced by continental forcing. The impact of the large Rewa River plume South of the main island of Viti Levu (Fiji) on the microbial processes i.e. carbon and nitrogen fluxes, fisheries richness or coral resources of the Fijian archipelago is unknown. SGLI imagery is helpful in describing ocean color South of Fiji. In order to examine the applicability of ocean colour algorithms for GCOM-C, in situ bio-optical and radiometric data were collected during the March-April 2022 SOKOWASA cruise. Typical mesotrophic waters with ranges of chlorophyll a concentration (Chla, 0.10-0.41 mg·m<sup>-3</sup>), MES (0.2 to 1.62 g·m<sup>-3</sup>),  $b_{bp,550}$  (5.7 10<sup>-4</sup>-0.0037 m<sup>-1</sup>) and  $a_{CDOM440}$  (0.013- 0.047 m<sup>-1</sup>) are found on a South-North gradient between open ocean and the coast. The remote sensing reflectance obtained using HOCR were inverted to retrieve Inherent Optical Properties (IOPs) for the empirical and semi-analytical (QAA, GIOP) algorithms and for OC3 for Chla. All IOPs could be derived from Chla (Case 1 waters). Results showed the capacity and usefulness of the derived products of SGLI (GCOM-C) to monitor the water quality of the Southern ocean South of Fiji. As concluded by bio-optical analysis, during the dry period experienced during SOKOWASA, mesotrophic waters extend far south of the Kadavu Island and small phytoplankton plumes issued from land are mostly formed by organic matter and may feed coral reefs.

**Keywords:** chlorophyll, algorithm, coral reef, Island Mass effect, ocean color, Fiji Islands, tropical Pacific Ocean, La Nina, sea surface reflectance

## 1. INTRODUCTION

Sea surface chlorophyll is a proxy of phytoplankton biomass and is a direct integrator for the nutrient status of water masses and chlorophyll monitoring by satellite greatly expands our knowledge of the functioning tropical waters ([1]). Oceans around the tropical islands of the Southwestern Tropical Pacific are characterized by a range of extremely oligo- to mesotrophic waters ([2], [3]). This so-called Island Mass effect (IME) has been largely investigated from satellite data ([4], [5]). Indeed, current algorithms such as OC3 for MODIS are suitable for oceanic waters where chlorophyll drives variability of bio-optical properties (absorption and backscattering) of the waters ([6]). Nevertheless, few studies have been conducted in order to properly analyze this IME.

In the area south of the southernmost island of Fiji, Viti Levu, bathymetry is steep and the island is bounded by a continental platform covered with coral reefs ([7], [8]). The oceanic biogeochemical environment south of these reefs is strongly influenced by meteorological events ([9]) and continental forcing ([10], [11]). The trophic state is related with spatial variations in currents around the islands and episodic river outputs linked to the impact of the large Rewa River plume in Laucala Bay ([12]). Nevertheless, the variability of carbon and nitrogen fluxes, fisheries richness of this region of the Fijian archipelago has not been investigated yet.

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The objective of SOKOWASA cruise (<https://doi.org/10.17600/18002025>) was to determine the extension and nature of the plume (if any) by acquisition of optical and biogeochemical data South of Fiji, with the aim of validating the OC3 algorithm for Chla, and GIOP (QAA) inversions of in situ and satellite SGLI reflectance. This is preliminary work allowing to use ocean color remote sensing as a tool for surveying the environment of this highly variable ecosystem.

## 2. MATERIAL AND METHOD

### 2.1 Study site characteristics

The study area lies South of the Southern island of Viti Levu, in the Southwestern Tropical Pacific from 18.7 to 18.1°S, and 178° to 178.5°E, with a continental platform with coral reefs. The SOKOWASA cruise was during a typical dry period in March-April 2022.

In March 2022 in Nadi, the air temperature average high was 28°C (with a record high of 33°C) and the average low was 23°C. On the northern Fiji, there was plenty of rainfall, with a total of 533mm over the month and an average of 17.16mm per day but only on the Northern part of Fiji, while on the southern coast of Viti Levu, rain was scarce (1, 0.4, 0.3, 8 mm rain at Suva station for the 27, 28, 29, 30 March 2022, with 50 mm on the 31rd March). The rain was then rare and the winds remained weak (< 10 knots) during the study ([11]).

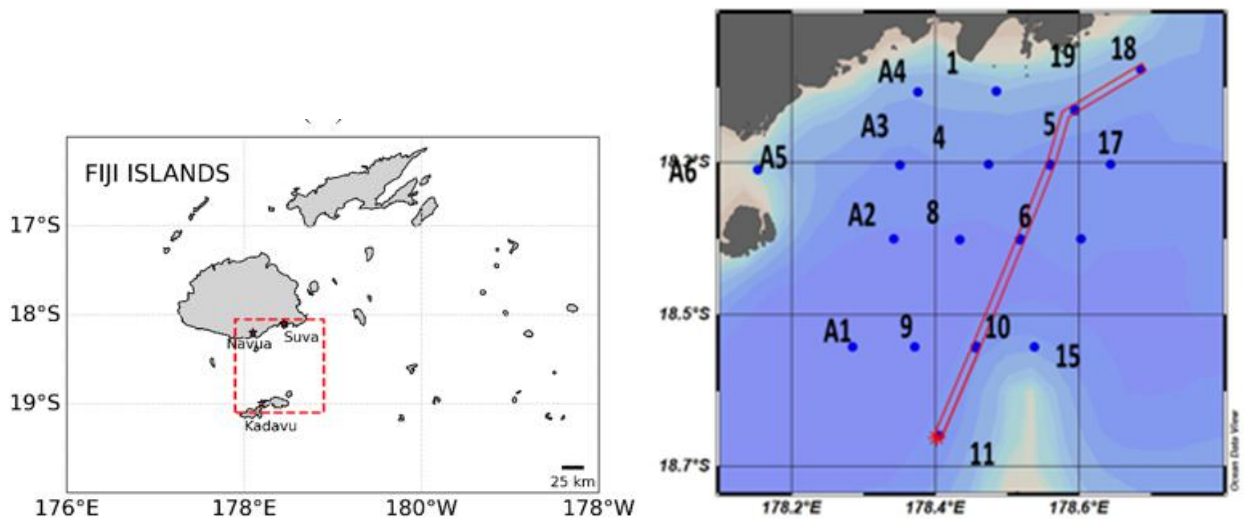


Figure 1. Map showing location of stations sampled during the SOKOWASA cruise March 27 – April 1, 2022 and coral reefs (Ocean Data View). Stations are indicated.

### 2.2 Sampling

Sampling included a network of 17 stations spaced ~ 2 km apart in in the ocean from Kadavu Island to Southern Viti Levu (Laucala Bay and Beqa) off the barrier reefs (22 March-1 April: Map Figure 1, blue circles). A total of 18 stations were sampled. A transect by a glider (SEA003) completed the cruise stations.

### 2.3 Optical parameters and discrete water samples

The cruise was designed to characterize the in situ apparent and inherent bio-optical inherent properties of waters (absorption and backscattering, IOPs) driving the remote sensing reflectance South of Fiji as well as pigment concentration of phytoplankton and suspended matter concentration.

### 2.3.1 Radiometric data

Radiometric data was collected using an in-water free-falling Satlantic profiler drifting at a large distance to avoid the influence of the boat shadow. The Satlantic free-falling profiler radiometer (Hyperpro-II) measures radiance between 350 and 800 nm (3.3 nm bandwidth). With this instrument radiometric data was obtained with in-water profiles of downwelling irradiance ( $E_d(\lambda, z)$ ) and upwelling radiance ( $L_u(\lambda, z)$ ). Data was pre-processed on board using the Prosoft software with the instrument calibration files, and some profile editions to eliminate noise (using tilt and velocity thresholds). These profiles were made at 12 stations.

### 2.3.2 In situ bio-optical data

Water sample was collected with Niskin bottles at different depths of the upper-water column and filtered onto 47 mm GF/F filters. Filtrations were performed immediately onboard at low vacuum pressure. The chlorophyll-a concentration (Chla) was determined by two methods: (i) using an adapted fluorometric method after 90% methanol extraction, and subtracting for pheopigments after acidification and (ii) by High Performance Liquid Chromatography (HPLC). We used the HPLC total Chla (TChla) as the reference value and the fluorimetric Chla to determine the standard deviation as an uncertainty metric. The mean percent difference between the two measurements was lower than 10% indicating good accuracy (Total HPLC Chla = 1,1 fluorimetric Chla,  $r^2=0,86$ , [6]. CDOM light absorption ( $A_{CDOM}$ ) from 250-750 nm was measured on board using the UltraPath method (World Precision Instruments Inc.), after filtration of the sample through a 0.2  $\mu\text{m}$  pore sized membrane filter, pre-washed in a 10% HCl solution and rinsed with MilliQ water. The blank reference was prepared to have similar salinity with addition of pre-combusted NaCl. The path length was adjusted to 2 meters according to each sample. Salinity and temperature corrections were performed following [13].

### 2.3.3 CTD and Hydrosat-6 profiles

*In situ* optical parameters are measured from an optical package (WET Labs, Inc.) including a chlorophyll fluorometer, a 10 cm pathlength beam transmissometer (at the wavelength 660 nm), and a Hydrosat-6 (HOBILabs, Inc.) which measures the optical backscattering at 6 wavelengths (442, 488, 510, 555, 620 and 670 nm). At each station, Conductivity Temperature Depth (CTD) casts down to 500 m recorded continuous vertical profiles of temperature and salinity. CTD data were checked for spurious values using the Seasoft software (Sea-Bird electronics, Washington, USA), binned at 1m intervals and presented for the top 300 m. CTD was equipped with temperature and conductivity Sensors, Wetlabs turbidity and fluorescence sensors, and a Beam attenuation meter (25 cm) Transmissometer, WET Labs C-Star. The method used to get the beam  $c_p(660)$  from the beam transmissometer is the one used in [14]. The method used to get  $b_{bp}$  from the Hydrosat-6 is described in [15]. The backscattering ratio was calculated as the ratio of the average of  $b_{bp}$  values at 620 and 670nm from the Hydrosat-6 to the beam  $c_p(660)$ .

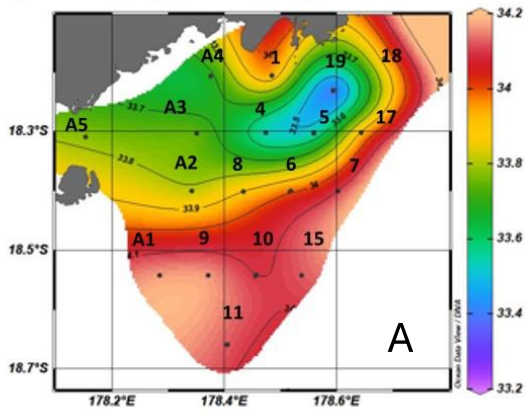
## 3. RESULTS

### 3.1 Spatial distributions of physical, biogeochemical and bio-optical parameters

The spatial distribution of physical parameters (temperature, salinity at 5 meters) obtained during the SOKOWASA cruise (27 March to 1st April 2022) is shown at Figure 2AB. All surface salinities are lower than 34.2, with the fresher waters (salinity < 32.5) at Station 19, and 34.5 at Station 5, in relation with rain and recent river outputs at the Southeastern coast of Viti Levu, the Rewa river at the south of the Suva city and the Vanua at the southern tip of the of studied area. Warmer waters than normal were advected from the Vanua river, while other patches may be tracers of preceding rain impact on the ocean.

Chla and turbidity concentrations decrease (Fig. 3ABCD) from coastal stations to offshore. They are maximum south of Laucala Bay (Stations 18 and 19). Concentrations higher than 0.4  $\text{mg m}^{-3}$  for Chl and higher turbidity (0.74 NTU) correspond to the fresher waters related to the fresh pocket there. DOC is maximum in the oceanic waters at the South and in the plume. PC is maximum at the coast.

Salinity, Practical [PSU] @ Pressure, Digiquartz [db]=4.00



Temperature [ITS-90, deg C] @ Pressure, Digiquartz [db]=4.00

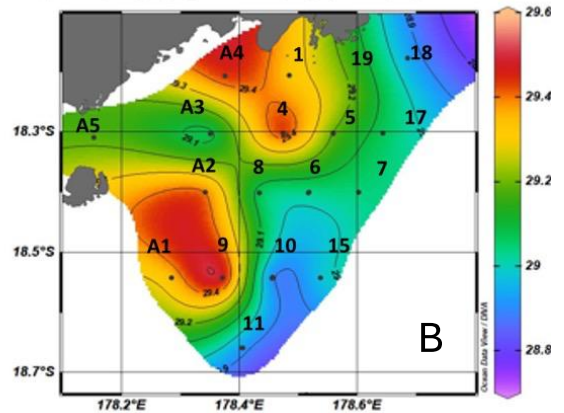
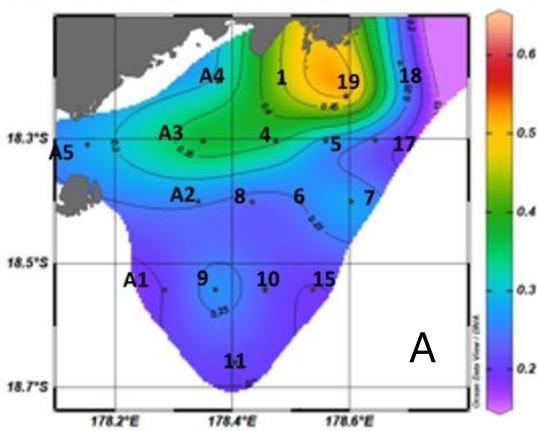
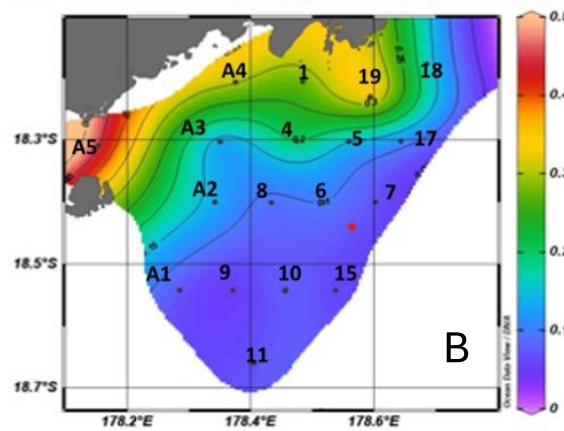


Figure 2. Spatial distributions of (A) Temperature, (B) Salinity for the SOKOWASA station network (27 March to 1 April).

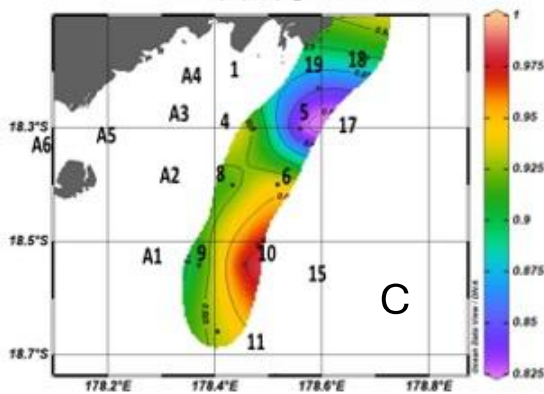
WET Labs ECO [NTU] @ Pressure, Digiquartz [db]=4.00



WET Labs ECO-AFL/FL [mg/m^3] @ Pressure, Digiquartz [db]=4.00



DOC [mgC/L] @ Bottles Fired=11.00



PC surface [μmol L-1] @ Bottles Fired=first

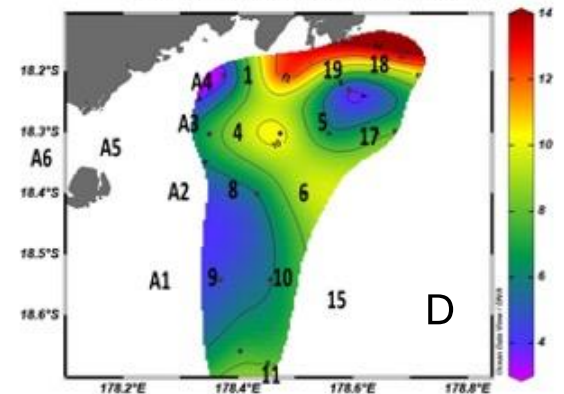


Figure 3. Spatial distribution of (A) Turbidity (NTU), (B) Chl a estimated by its Fluorescence (C) DOC, and (D) PC for the network (27 March to 1 April 2022) of the SOKOWASA cruise.

Regarding the optical parameters (Fig 4 ABC), spatial distributions of  $A_{CDOM(442)}$  and  $b_{bp}(440)$  slightly differ. The plume of high  $A_{CDOM(442)}$  is found at stations 19 ( $> 0.45 \text{ m}^{-1}$ ) and corresponds to the fresher waters as defined by a salinity lower than 33.4. The distribution of  $b_{bp}(442)$  shows a similar pattern than Chla fluorescence. There is a strong increase of  $b_{bp}(442)$  in the freshwater plume (St 4, 5 and 19). This freshwater plume shows values higher than observed in the rest of the southern waters (at station 19:  $0.0066 \text{ m}^{-1}$ ). The maximal values of  $A_{CDOM(442)}$  are found in the vicinity of the coral reef south of Laucala Bay ( $0.047 \text{ m}^{-1}$ ) at stations 18 and 19, probably under the influence of fresh riverine waters as already shown ([11]). The distribution of  $c_p(660)$  mimics the one of the  $b_{bp}(442)$  with the highest values in the chlorophyll-rich plume ( $C = 0,75 \text{ m}^{-1}$ , Station 19) and of the turbidity of the CTD (Figure 3A).

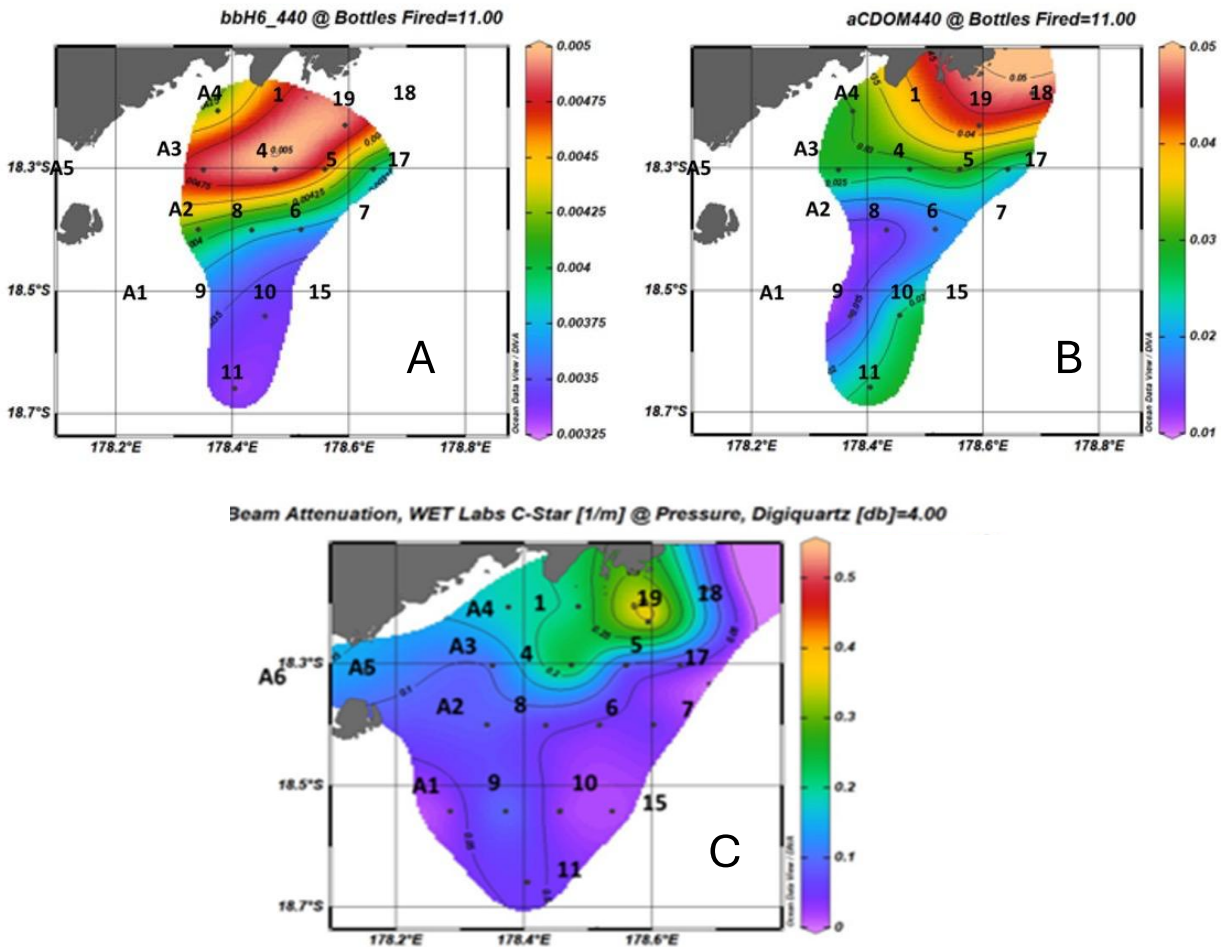


Figure 4. Spatial distribution of (A)  $b_{bp}440$ , (B)  $A_{CDOM(442)}$ , (C)  $c_p(660)$  (27 March to 1<sup>st</sup> April 2022 SOKOWASA cruise).

In situ values of the  $b_{bp}555$  and  $a_{dg}440$  are well correlated with measured Chla whatever the Chla method of determination (Figure 5 A,B and Figure 5 C,D). There is a satisfying correlation between  $b_{bp}555$  and the  $c_p(660)$  the beam-C of the CTD (Figure 5E).



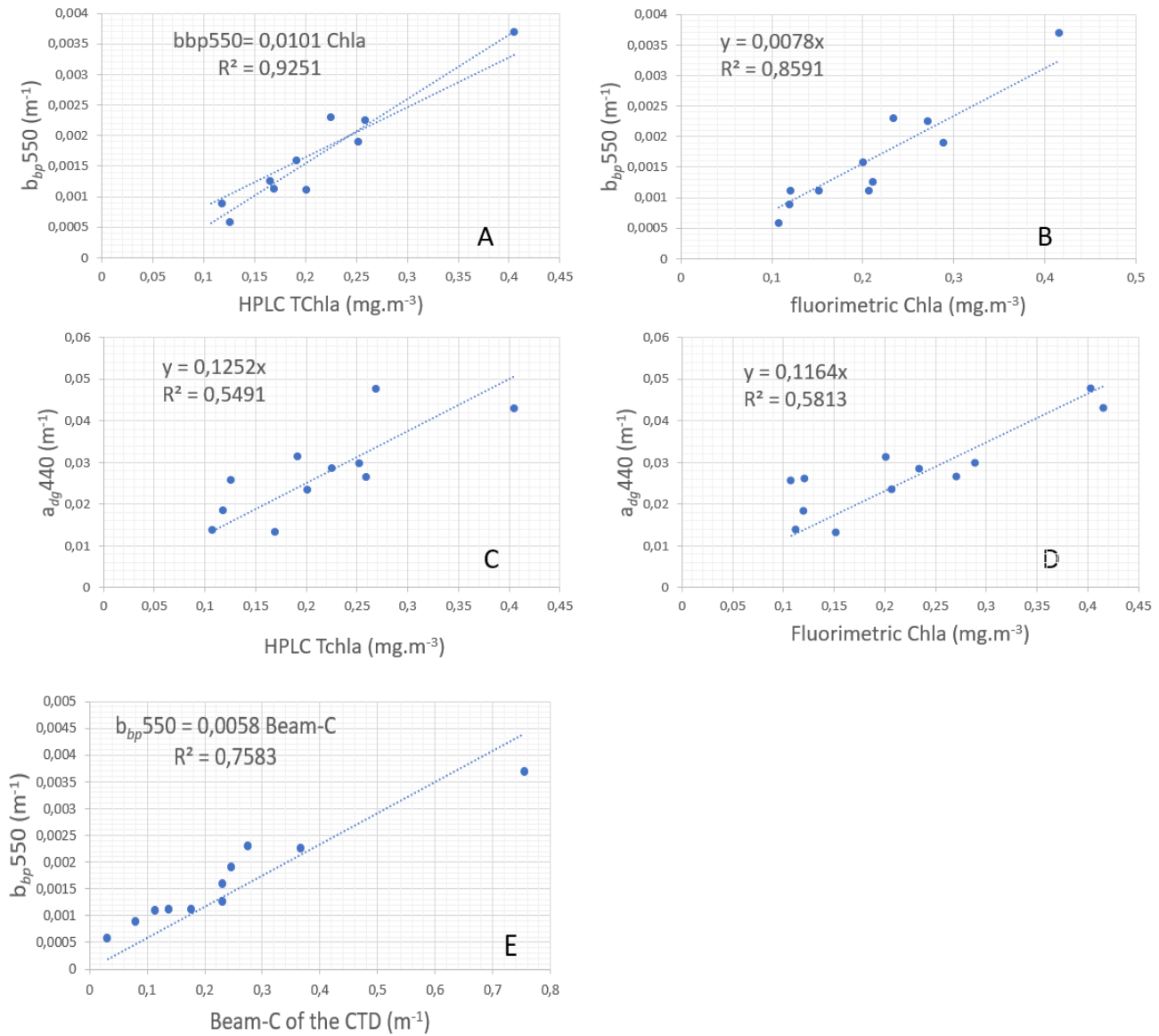


Figure 5. Relationship between in situ Hydrosat particulate backscattering coefficient at 550 nm and HPLC-Tchla Chlorophyll and B) fluorimetric Chla) C) relationship between in situ  $a_{dg440}$  and HPLC-Tchla Chlorophyll and (D) fluorimetric Chla) E) relationship between Hydrosat-6 measured particulate backscattering coefficient at 550 nm and the beam-C of the CTD.

### 3.2 Inversion of Rrs

The in situ hyperspectral Rrs spectra are typical of mesotrophic waters with a range at 400 nm of  $0.0118 \text{ sr}^{-1}$  for the clearest station and  $0.0049 \text{ sr}^{-1}$  for the most turbid station (station 19) (Figure 6). The inversion of Rrs by GIOP model provides spectra of IOPS  $a_p$ ,  $a_{ph}$ ,  $b_{bp}$  and  $a_{dg}$  (Figure 7 top) and results by the QAA inversion model are similar than the GIOP inversion model (Figure 7 bottom).

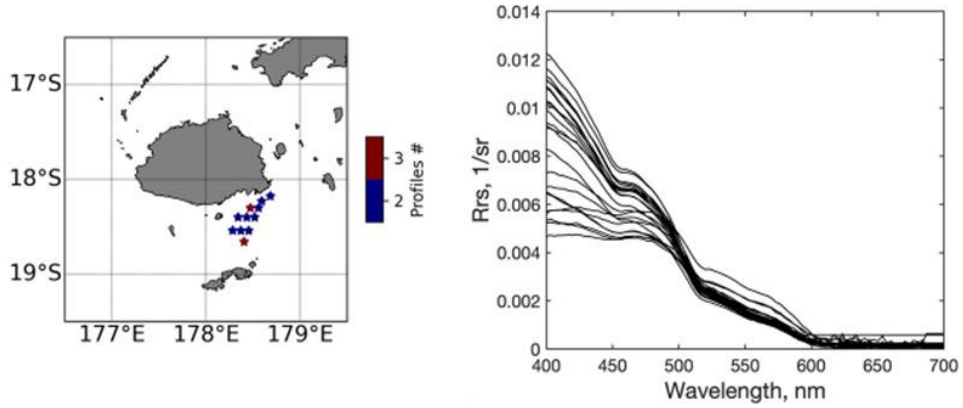


Figure 6. HOCR spectra obtained with the SATLANTIC HOCR profiler at the SOKOWASA station South of Fiji.

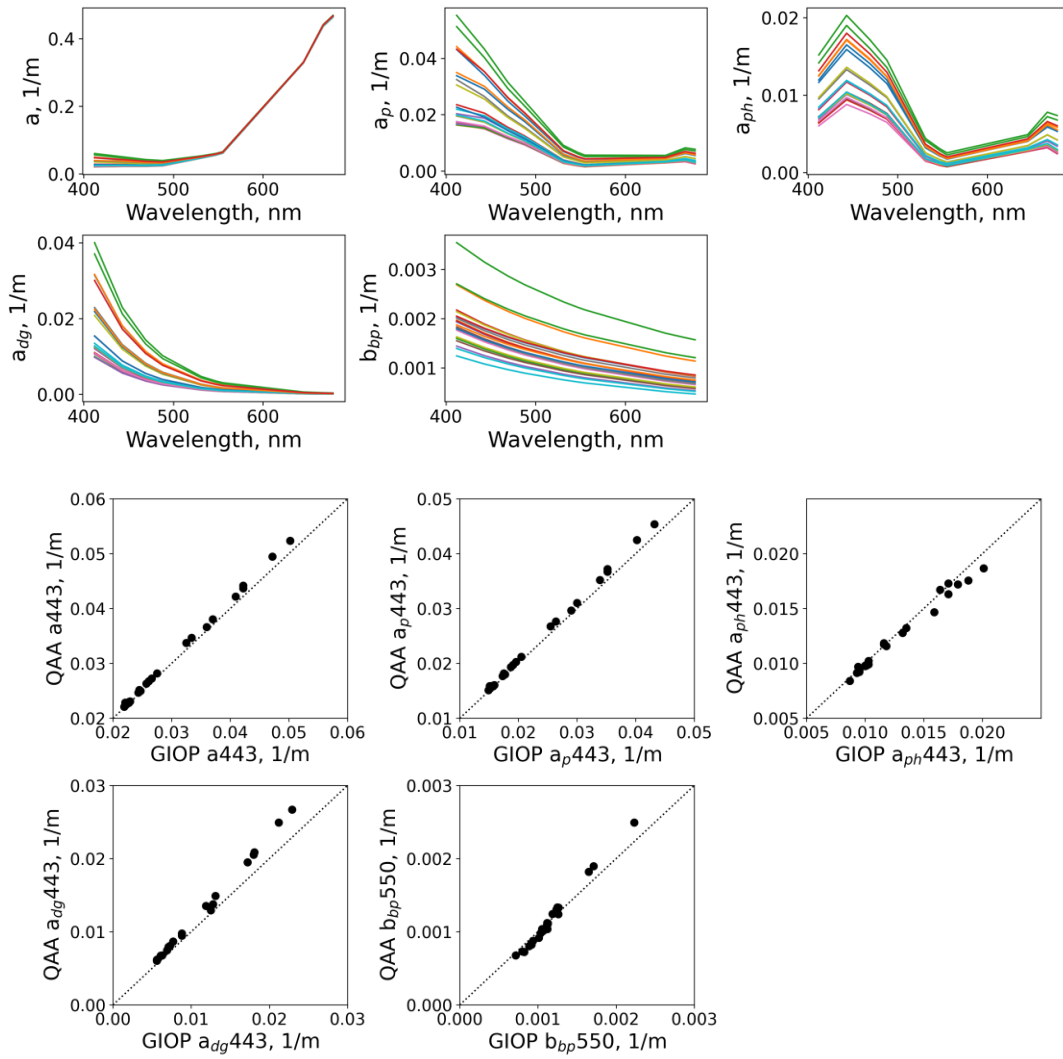


Figure 7. A) Spectra of retrieved GIOP IOPIs of  $a_p$ ,  $a_{ph}$ ,  $b_{bp}$ , and  $a_{dg}$ , B) comparison between GIOP and QAA inversions for each parameter.



Considering IOPs, only GIOP inversion results will be discussed (see Figure 8). As for the backscattering coefficient, we averaged in situ data over an attenuation length, in order to avoid the influence of perturbations of the signal as measured by the HydrosCat-6 profiler in the first 5 meters. The performance for retrieving  $b_{bp}$  depends on the wavelength considered. Correlation was better at 488nm than at 550 nm ( $r^2=0.78$  for 488 nm versus  $r^2=0.39$  for 550 nm). There is still an overestimation by GIOP of the in situ backscattering coefficient at all wavelengths. with slopes for  $b_{bp488}$  of 1.63 and for  $b_{bp555}$  of 1.52. The performance of the inversion of CDOM is poor as the correlation between inverted  $a_{dg}$  and measured  $A_{CDOM}$  at 412 nm is less than 0.4.

While regressions coefficients are higher than 0.5, it exists huge differences between GIOP retrievals and measurements (overestimation for  $b_{bp}$  and underestimation for  $A_{CDOM}$ ), despite the fact that we averaged in situ data over an attenuation length – and that profiles do not vary strongly over the 0-20m surface layer. The discrepancy obtained for the retrieval of IOPS by the GIOP model must then be explained by the fact that the relationships between  $b_{bp}$  and Chla or  $a_{cdom}$  and Chla in mesotrophic waters during SOKOWASA are different from those used by GIOP.

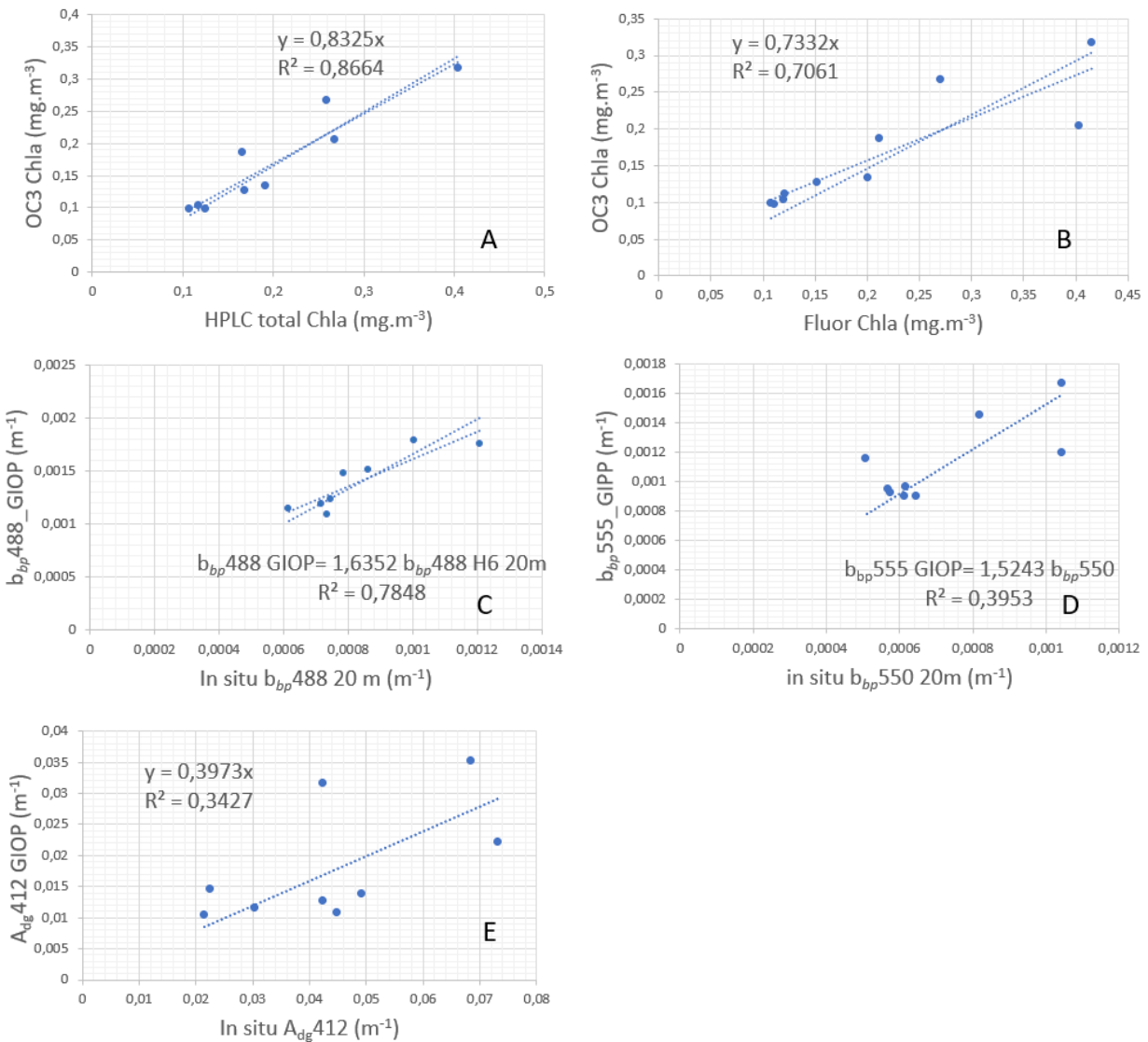


Figure 8. AB) Chla retrieved from OC3 vs Chla analyzed by 2 methods, CD) IOPS retrieved from the GIOP inversion model for the in situ backscattering coefficients at 488 and 550 nm, and for E)  $a_{dg412}$ .

### 3.3 GCOM-C Rrs product quality in Southern Fijian waters

Geophysical Data from SGLI are disseminated in in-water properties (IWPR) containing derived chlorophyll-a concentration, absorption coefficient by colored dissolved organic matter (CDOM), and the concentration of total suspended matter (TSM). The clearest image corresponding to the SOKOWASA cruise was for 03/04/2022 and the three GCOM-C products extracted for the studied SOKOWASA area are shown at Figure 9 ABC. GCOMC values of the three associated variables were extracted at the latitude/longitude of the 12 stations.

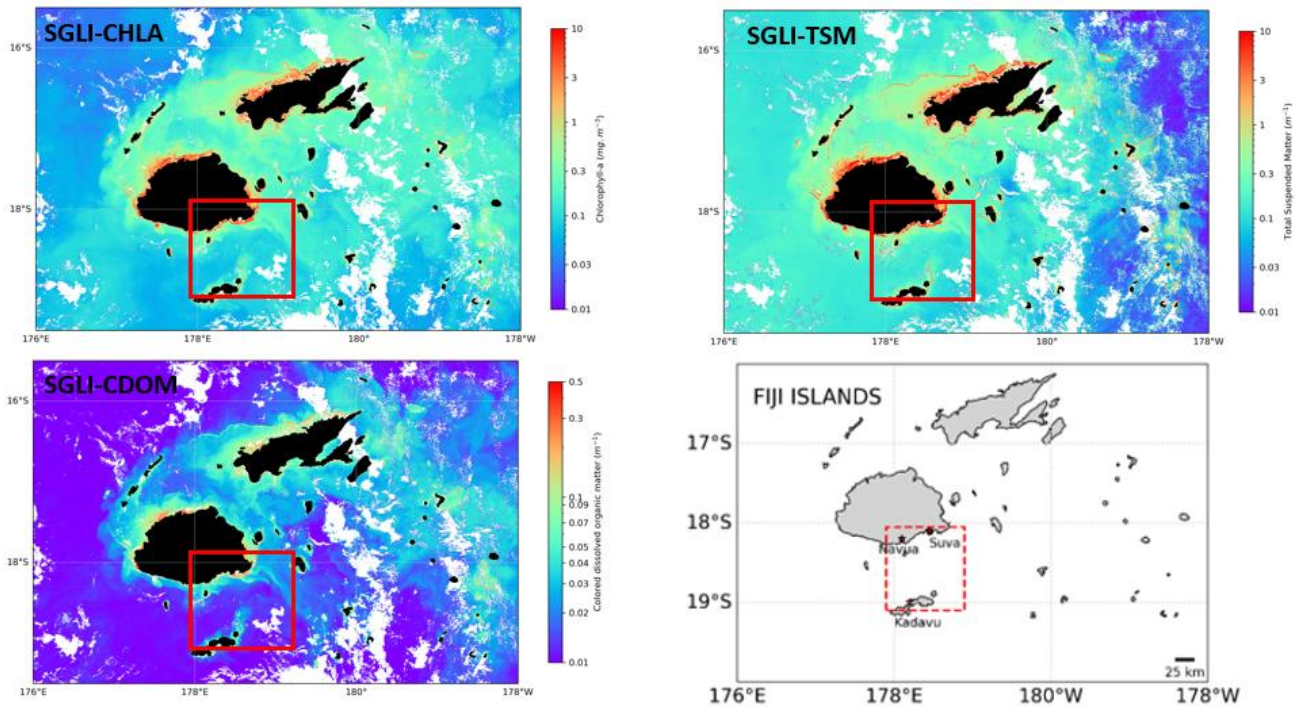


Figure 9. SGLI products for GCOMC: April 3, 2022. A) Chla, B) TSM, C) ACDOM, D) MAP of Fiji islands.

### 3.4 Performance of OC3 algorithm for the SOKOWASA cruise

There are satisfying correlations for Chla as SGLI-CHLA is 0,6 or 0,7 x *in situ* Chla according to the methodology considered for Chla analysis but SGLI strongly underestimates chlorophyll (Figure 10AB). There is no correlation for SGLI-TSM with the backscattering at 488 (as chosen as an index of turbidity). *In situ* CDOM is well retrieved ( $r^2=0,75$ ) though SGLI strongly underestimates this IOP (slope of 0,40) which is in fact similar to that obtained by inverting HyperOCR Rrs for  $a_{dg}$  (slope of 0.39) (Figure 10C). The strikingly good regression coefficient obtained for SGLI-ACDOM compared to measured  $a_{dg}$  is an excellent result considering the small range of values of acdom in oligo- to mesotrophic oceanic environment South of Fiji (Figure 10C). As there was no *in situ* value of TSM, the  $b_{bp,488}$  coefficient was chosen instead as an index of turbidity as in [6]. The correlation between SGLI-TSM and the  $b_{bp,488}$  (Figure 10D) was low.

There is also a strong correlation between SGLI TSM and SGLI-CHLA (Figure 11A), and between SGLI ACDOM and SGLI-CHLA products (Figure 11B).

To summarize our results:

- SGLI products can be used to retrieve Chla, ACDOM less for TSM. The performance for ACDOM is high, given to the methodological difficulty of measuring CDOM values in tropical waters. There is a strong autocorrelation between SGLI TSM CDOM with Chla.

- It must be stressed that SGLI retrievals and in situ measurements are not collected at the same time, i.e., comparisons are limited and can only give a trend. It is difficult to justify that there is no variability over several days, even during a dry period with low continental outputs.
- This suggests that the bio-optical relationships measured in the South Fijian ocean are different from those used in the inversion algorithms developed for the global ocean (as SGLI uses an algorithm similar to GIOP).

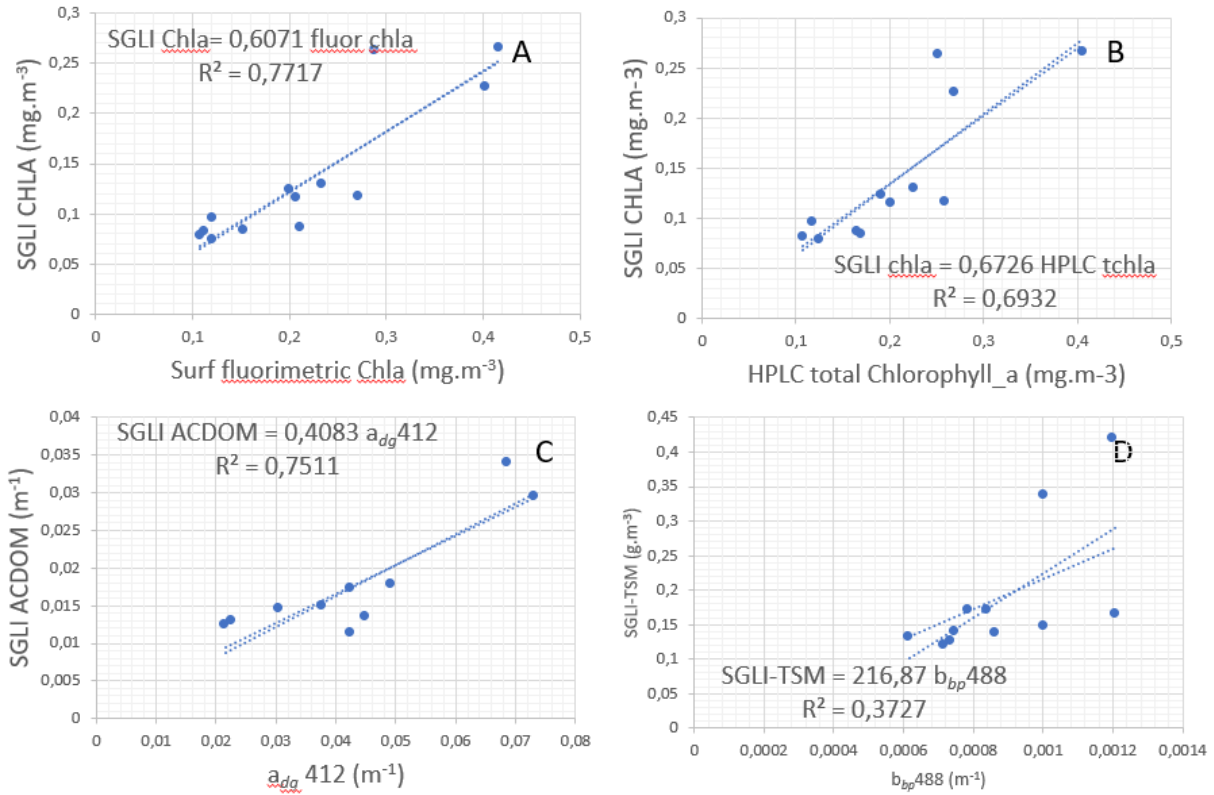


Figure 10. Performance of inversion of SGLI products. AB) for Chla, vs in situ Chla analyzed by 2 methods, CD) for ACDOM and TSM (the  $b_{bp488}$  coefficient was chosen as an index of turbidity).

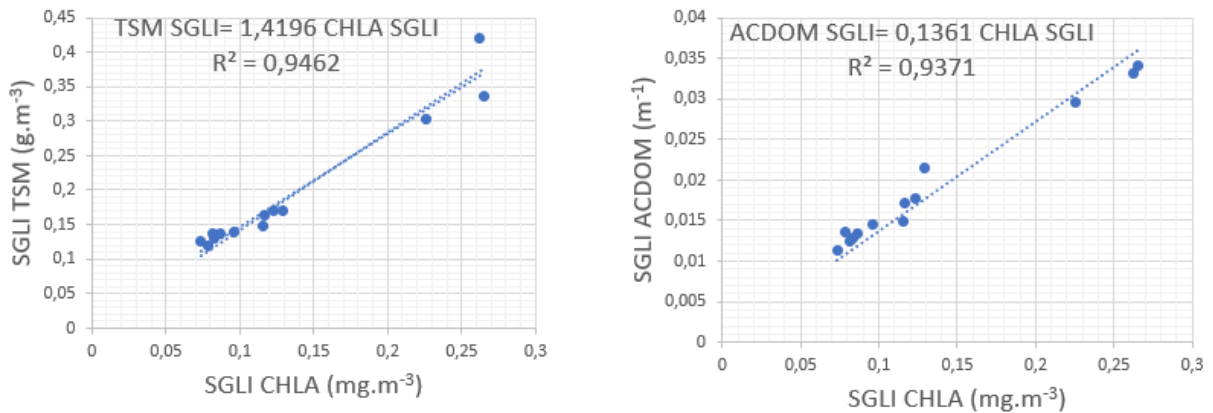


Figure 11. Correlation between the three SGLI products.

## 4. CONCLUSIONS

During the dry period in March-April 2022, mesotrophic waters ( $> 0.1 \text{ mg}\cdot\text{m}^{-3}$ ) with salinities less than 34.2, were found as far south as Kadavu Island, more than 30 miles from land, suggesting the influence of preceding continental riverine outputs in the South of Viti Levu.

Chlorophyll-a (Chl a) was the primary driver of variability of optical properties. Strong correlations between in situ optical measurements (IOPS) and Chl a indicate a minimal influence of mineral particles from the Rewa and Navua Rivers in coastal plumes.

The GIOP inversion model performed well for Chl a retrieval but was less accurate (overestimated), for backscattering particularly at green wavelengths. The model performed poorly for chromophoric dissolved organic matter (CDOM).

The SGLI satellite products were effective for Chl a retrieval and ACDOM (underestimated), but not for total suspended matter (TSM). The ACDOM retrieval performance was notably good despite the difficulty of measuring low CDOM values in tropical waters. Indeed, the performance suffered due to a large lag (over 3 days) between satellite imagery and in situ measurements. A strong autocorrelation was found between SGLI products for TSM, CDOM, and Chl a,

The role of Chl a in driving water quality variability, and the strengths and limitations of remote sensing tools like GIOP and SGLI for monitoring coastal and oceanic conditions in the region are demonstrated. These results will be confirmed by the exploitation of the SEA003 glider optical data along the Kadavu-Viti Levu transect.

The great coral reefs biodiversity around Beqa and Kadavu islands and on the East of Viti Levu island, depends on the oceanic waters transparency. South of Fiji, mesotrophic waters driven by chlorophyll characterize plumes during dry period, with a nul influence of coastal minerals, which may be favorable for the tropical food chain. Surveys of the influence of ocean on coral reefs is essential to maintain healthy food resources for Pacific countries communities dependent on coastal marine resources.

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