

Remote sensing of the southern ocean by MERIS, MODIS, SeaWiFS and ENEA Lidar

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Oceanic phytoplankton plays a major role in climate regulation. This explains the international efforts in space monitoring of chlorophyll-a concentration, i.e. the main indicator of algal biomass. In this study three radiometers (MERIS, MODIS and SeaWiFS), aboard satellites, and the ENEA lidar, aboard a ship, are intercompared. Important discrepancies among the radiometers have been observed. In particular, MERIS can be up to 100% apart from MODIS and SeaWiFS. This difference reduces to about 35% if MERIS is calibrated with the ENEA lidar. Those results confirm the unavoidable need of precise measurements of chlorophyll-a concentration in close proximity to the sea surface. Moreover, it is demonstrated that regional calibrations of satellite radiometers lead to more accurate estimates of oceanic phytoplankton.

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1. Introduction

The debate on climate, as probably climate itself, is warming year by year. It is clear that oceanic phytoplankton is a major sink for the more important greenhouse gas, carbon dioxide. Conversely, the role of cold regions in this hot problem needs a deeper understanding. For this reason, we played the game of comparing the chlorophyll-a concentration measured by our lidar and retrieved by MERIS, MODIS and SeaWiFS in the Southern Ocean.

MERIS (Huot et al. 2002), MODIS (Esaias et al. 2002) and SeaWiFS (Hooker et al. 1992) are the more relevant ocean color satellite radiometers and determine the chlorophyll-a concentration from the blue-to-green ratio of the sunlight backscattered by the sea surface.

The ENEA lidar fluorosensor (ELF) (Barbini et al. 2001) operates aboard the research vessel Italica and is based on laser induced fluorescence: chlorophyll-a is detected measuring its emission at 680 nm after excitation by a frequency-tripled Nd:YAG laser at 355 nm. Thanks to narrowband filtering and electronic gating, LIF signals do not need corrections for radiometric and spectral characteristics of solar irradiance and surface reflectance. Furthermore, due to the short distance from the target, atmospheric effects are negligible. This explains why ELF data can be regarded as sea truth and have been used for the satellite calibration (Barbini et al. 2003).

The simultaneous measurements of chlorophyll-a by MERIS, MODIS, SeaWiFS and ELF have been compared during the 18th Italian expedition in Antarctica, carried out from January 5th to March 4th, 2003. The region under study has been named Ross Sea Sector (RSS) and has been defined as the zone of Southern Ocean from the coast of Antarctica north to 50 S latitude in the 160 E – 130 W

interval. The definition of RSS has been chosen in order to compare our study with literature data (Arrigo et al. 1998).

2. Methods

At first, monthly data of MERIS, MODIS and SeaWiFS have been compared. The standard MERIS chlorophyll-a product "Chl2" (for all kind of waters) has been used. Only MODIS-Aqua chlorophyll-a data have been downloaded because MODIS-Terra chlorophyll-a data are no longer available. For the sake of simplicity, it has been decided to resample all pixels so that they have the same resolution and projection of SeaWiFS Level 3 (L3) Standard Mapped Image (SMI), i.e. the resolution of 5'16" × 5'16" and the equidistant cylindrical projection. Resampling is very easy for MODIS because four MODIS pixels fall exactly in one SeaWiFS pixel. For MERIS, only daily Level 2 (L2) data were available and MERIS monthly L3 data were obtained simply averaging all the MERIS L2 data falling in that month in a pixel of 5'16" × 5'16" corresponding to a SeaWiFS pixel. This procedure has been applied both "not taking into account" and "taking into account" the quality flag, providing us with MERIS "all qualities" and MERIS "best quality" products, respectively.

The chlorophyll-a maps are given in Fig. 1. White zones correspond to missing values (clouds or ice), land is represented in grey. In January and February ice-free regions are present near ice shelves and Cape Adare (about 72° S, 170° E), while they close nearly completely in March. Ice-free regions and the Antarctic Convergence (around 65° S) show the largest phytoplankton blooms, with chlorophyll-a up to about 10 mg m⁻³.

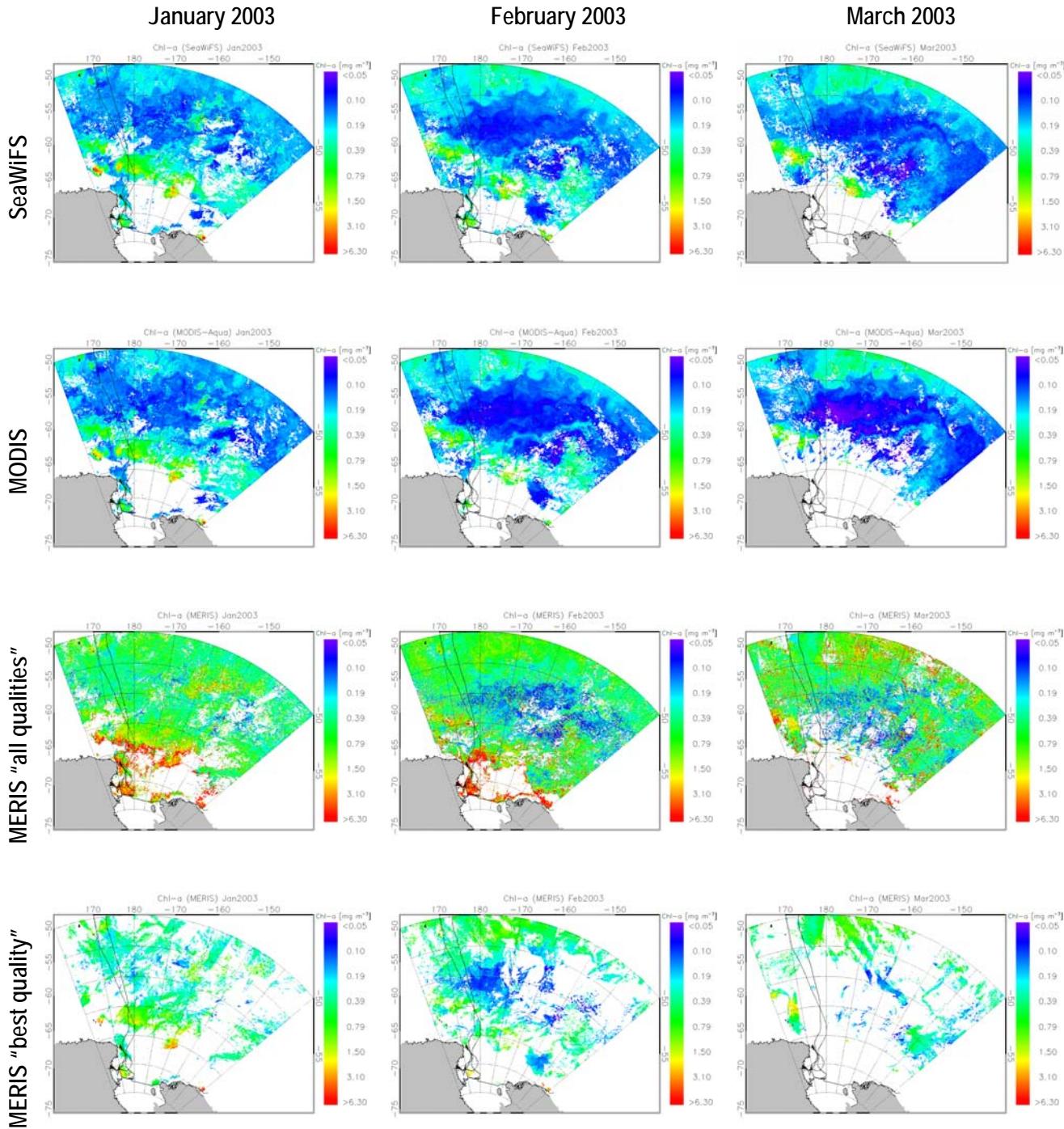


Fig. 1. Chlorophyll-a measured in RSS by SeaWiFS, MODIS and MERIS from January to March 2003. The black line is the cruise track of ELF.

A first sight at the difference among the sensors indicates that:

- SeaWiFS and MODIS have similar values and coverage (although in March SeaWiFS has slightly higher values in the central part of RSS

and a better coverage in the southern part of RSS).

- MERIS “all qualities” products, with respect to SeaWiFS and MODIS products, exhibit higher values, especially in regions closer to ice (southern part of RSS) where SeaWiFS and

MODIS measurements are more sparse. Unfortunately, there is a noticeable discrepancy between the European sensor and the American sensors. If only MERIS "best quality" products are retained the discrepancy reduces but, at the same time, also MERIS coverage becomes less extended (lower than that of SeaWiFS and MODIS). In the following, the more cautious approach will be followed, i.e. only MERIS "best quality" products will be compared to SeaWiFS and MODIS products.

The percent difference among the chlorophyll-a concentrations sensed by SeaWiFS, MODIS and MERIS is

given in Fig. 2. The formula giving the percent difference (D) between the chlorophyll-a concentration sensed by sensor 1 (C₁) and sensor 2 (C₂) is simply:

$$D = \frac{C_1 - C_2}{C_1}.$$

The general consensus between SeaWiFS and MODIS is confirmed, with the exception of the central part of RSS in March. Also the observation that MERIS values are generally higher is corroborated.

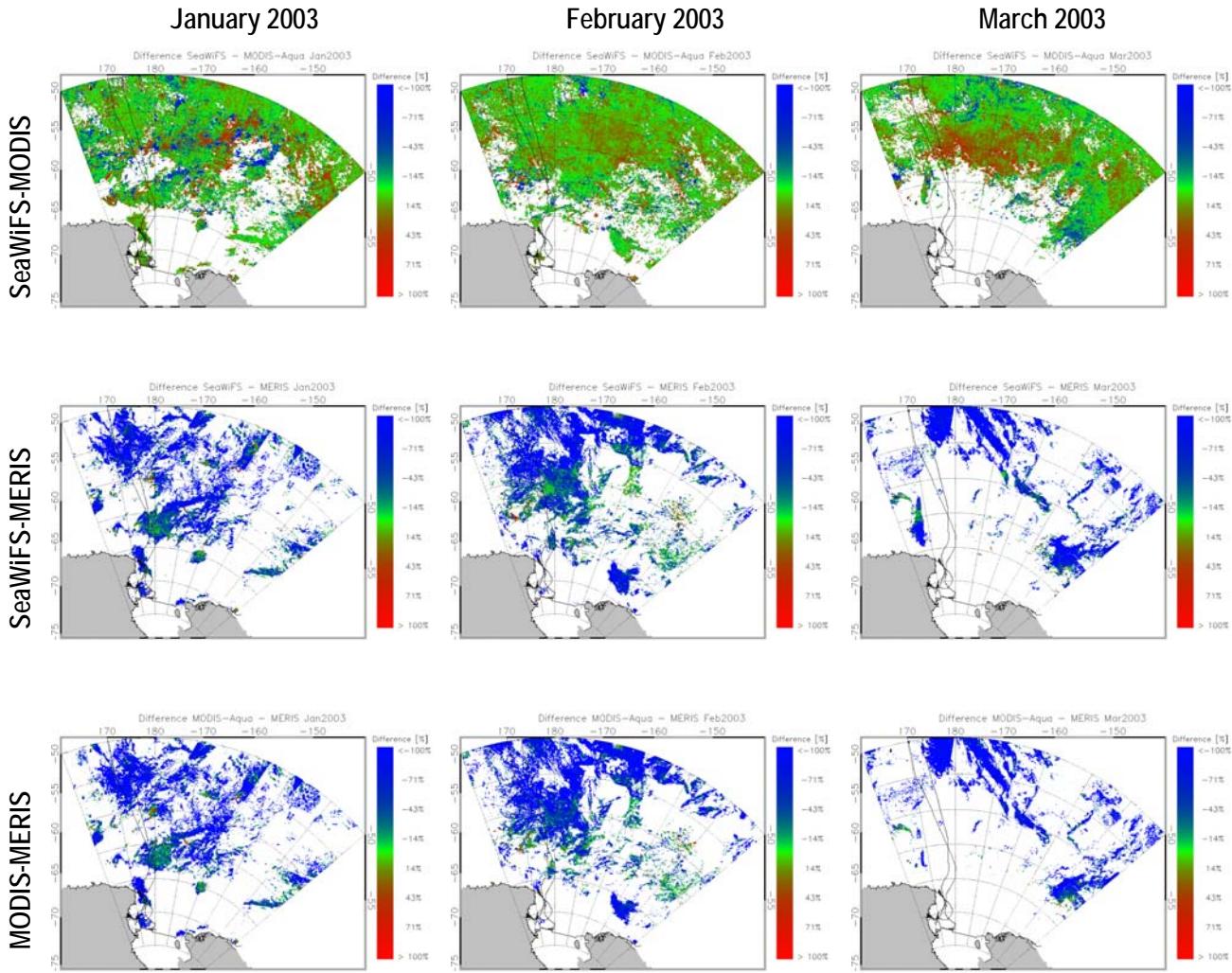


Fig. 2. Percent difference among the values of chlorophyll-a sensed by SeaWiFS, MODIS and MERIS from January to March 2003.

After the intercomparison among MERIS, MODIS and SeaWiFS, those sensors have been matched up with ELF. Some processing was necessary to achieve this task. At first, all the ELF measurements falling in a SeaWiFS pixel were averaged, thus representing a nearly straight

track (length: ~ 10 km, width: ~ 0.1 m) acquired in about 20 minutes. Eventually, the measurements carried out by lidar and SeaWiFS were considered concurrent if the ship track was acquired in the same day as the remote sensed pixel. MERIS and MODIS daily L3 data with the

SeaWiFS resolution and projection have been obtained analogously to MERIS and MODIS monthly L3 data (see above). Unfortunately, the resolution of SeaWiFS and ELF differs:

- In time, since the acquisition interval of ELF is short compared to 1 day.
- In space, because the square of about $9 \text{ km} \times 9 \text{ km}$ observed by SeaWiFS is larger than the track of about $10 \text{ km} \times 0.1 \text{ m}$ sensed by ELF, even if the track is inscribed in the square.

That dissimilarity in temporal and spatial resolutions can be responsible for part of the disagreement between satellite radiometers and ELF. In many occasions, ELF was able to carry out measurements when SeaWiFS was not. This partial failure to obtain results is due to cloud coverages and ice debris.

The comparison between satellite radiometers and ELF shows the following general behavior (Fig. 3):

- In the Julian Days from 5 to 15 (while ELF was in the open ocean), MERIS is higher than SeaWiFS, MODIS and ELF, while those latter three instruments mutually agree.
- In the Julian Days from 15 to 50 (while ELF spanned the Ross Sea, especially near the ice shelf) MERIS is higher than ELF. This latter instrument, in turn, is higher than SeaWiFS and MODIS.
- In the Julian Days from 54 to 58 (while ELF was in coastal zones) ELF agrees better with MERIS and is higher than SeaWiFS and MODIS.
- In the Julian Days from 59 to 63 (while ELF was in the open ocean), there is a more messy behavior: ELF is higher than SeaWiFS and MODIS, while MERIS spans the entire interval between low and high values.

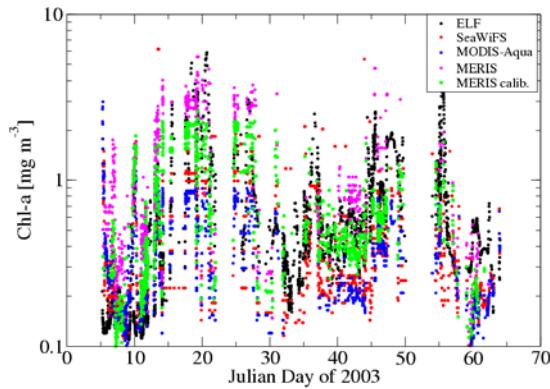


Fig. 3. Comparison among the values of chlorophyll-a sensed by ELF, SeaWiFS, MODIS and MERIS (standard or ELF-calibrated) along the cruise track of ELF.

Those observations could indicate that SeaWiFS and MODIS are more accurate than MERIS in the open ocean, while the European sensor performs better than the American sensors in the coastal zone. Anyway, MERIS is far from SeaWiFS and MODIS in a large part of RSS. In

order to solve that problem, the MERIS bio-optical algorithm has been calibrated, following a procedure already used for SeaWiFS and published elsewhere (Barbini et al. 2003). Briefly, the ELF-calibrated MERIS bio-optical algorithm has been based on the linear fit of the log-log plot of the ELF chlorophyll-a concentration versus the MERIS 490-560 band ratio, i.e.:

$$\log_{10} C = a_0 + a_1 R,$$

where C is the chlorophyll-a concentration in mg m^{-3} and:

$$R = \log_{10} \frac{Rrs(490)}{Rrs(560)},$$

$Rrs(490)$ and $Rrs(560)$ are the remote sensing reflectance at 490 and 560 nm, respectively, and R is called the 490-560 band ratio. The parameters of the ELF-calibrated MERIS bio-optical algorithm are summarized in Table 1.

Table 1. Parameters of the ELF-calibrated MERIS bio-optical algorithm.

Number of pixels	a_0	a_1	Correlation coefficient "r"
104	0.47 ± 0.40	-2.6 ± 1.0	0.725

As it could be expected, the agreement between ELF and MERIS is better when the radiometer is calibrated with the lidar (Fig. 3). Actually, the ratio between the values of chlorophyll-a sensed by a radiometer and by the lidar along its cruise track (Fig. 4) is closer to 1 for ELF-calibrated MERIS than for SeaWiFS and MODIS. This could indicate that ELF-calibrated MERIS perform better than SeaWiFS and MODIS in RSS during the 18th Italian expedition in Antarctica.

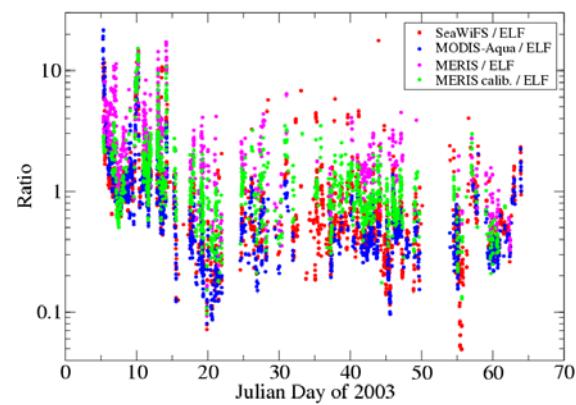


Fig. 4. Ratio between the values of chlorophyll-a sensed by SeaWiFS, MODIS and MERIS (standard or ELF-calibrated) and by ELF along the cruise track of ELF.

3. Discussion

SeaWiFS, MODIS and ELF-calibrated MERIS can now be used to evaluate the chlorophyll-a concentration

during the austral summer 2002-2003. Unfortunately, MERIS data do not exist before December 2002 and our study will be limited to the four months from December 2002 to March 2003.

Fig. 5 shows the maps of average chlorophyll-a. It is confirmed the behavior observed with monthly products:

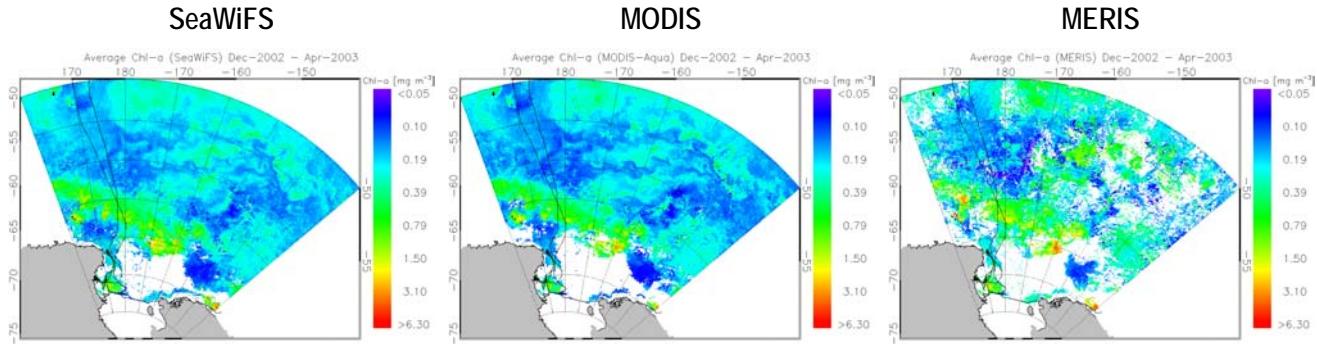


Fig. 5. Average chlorophyll-a measured in RSS by SeaWiFS, MODIS and ELF-calibrated MERIS from December 2002 to March 2003.

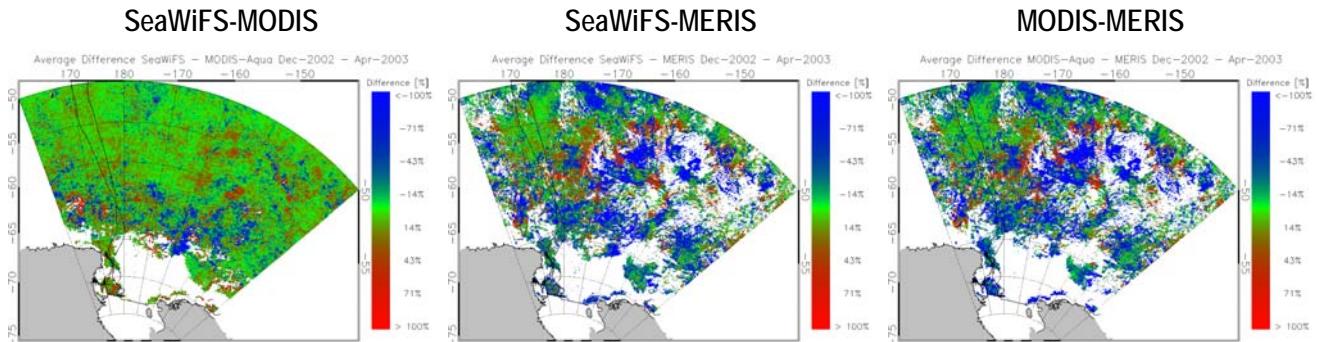


Fig. 6. Average percent difference among the values of chlorophyll-a sensed by SeaWiFS, MODIS and ELF-calibrated MERIS from December 2002 to March 2003.

The average difference among the chlorophyll-a values measured by SeaWiFS, MODIS and MERIS is given in Fig. 6. In almost all pixels, SeaWiFS and MODIS show discrepancies smaller than 35%. On the contrary, the European sensor disagrees frequently and substantially with the American sensors. Nevertheless, after the ELF-calibration of the MERIS bio-optical algorithm, discrepancies have both signs (with the standard MERIS products, almost all of them were negative, see Fig. 2). It is difficult to associate the differences to a specific geographic or biological province. In order to get more information on the difference among SeaWiFS, MODIS and MERIS, histograms (Fig. 7) and scatter plots (Fig. 8) of the average chlorophyll-a values measured by those sensors have been drawn.

ice-free regions and the Antarctic Convergence show the largest biomass. The coverage of SeaWiFS is slightly larger than that of MODIS (see also Table 2). Conversely, the European sensor measure significantly less pixels than the American sensors.

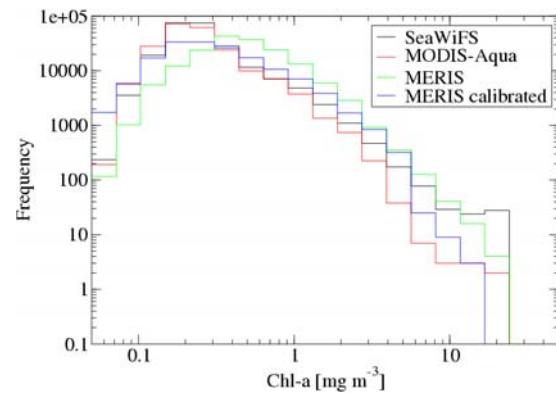


Fig. 7. Histograms of the average chlorophyll-a measured in RSS by SeaWiFS, MODIS, standard MERIS and ELF-calibrated MERIS from December 2002 to March 2003.

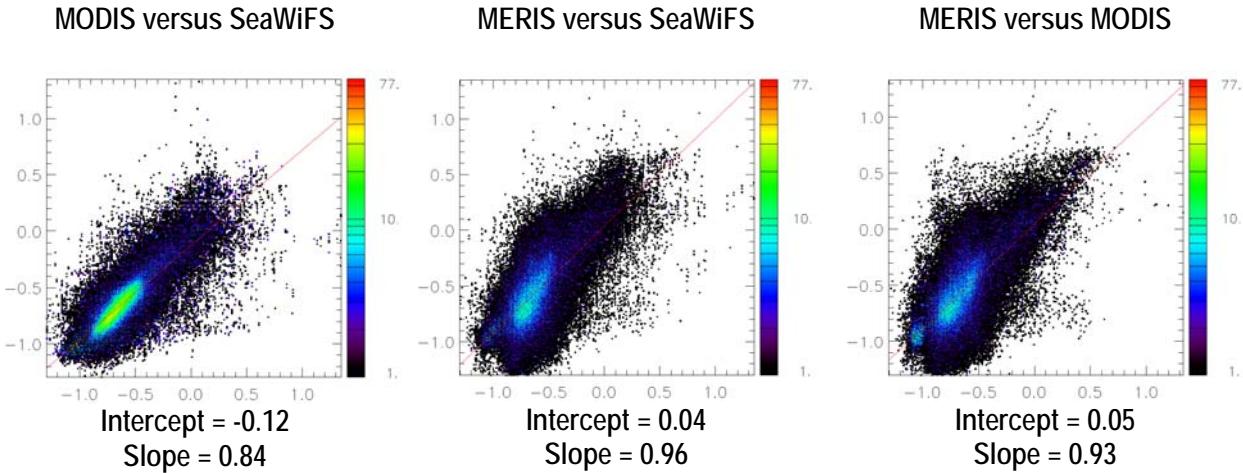


Fig. 8. Scatter plots of the logarithm of the average chlorophyll-a measured in RSS by SeaWiFS, MODIS and ELF-calibrated MERIS from December 2002 to March 2003.

The histograms of chlorophyll-a indicate that the largest differences in frequency between the European sensor and the American sensors can be observed for small chlorophyll-a ($< 0.3 \text{ mg m}^{-3}$). Fig. 7 shows also the correction operated passing from standard to ELF-calibrated MERIS bio-optical algorithm: the number of high chlorophyll-a pixels ($> 0.3 \text{ mg m}^{-3}$) was reduced, while that of low chlorophyll-a pixels ($< 0.3 \text{ mg m}^{-3}$) was increased.

The scatter plot of SeaWiFS versus MODIS shows the good agreement between them. Nevertheless, the linear fit is quite different from the identity (i.e. the straight line with intercept = 0 and slope = 1). This is explained by the points in the bottom-right part of the scatter plot (characterized by high SeaWiFS chlorophyll-a) that bend the fit. Anyway, the appearance of the scatter plot and the value of the slope of this study are similar to those found by Kwiaktowska (2003) in the World Ocean. The larger discrepancy in the intercept can be ascribed to two reasons: the first one is that we focused on a specific oceanographic province, the second one is that we did not limit ourselves to open ocean and clear atmosphere conditions. In the first case, regional calibrations of the chlorophyll-a algorithms could increase the agreement, as already shown in temperate regions by Barbini et al. (2004). The points of the scatter plots of the European sensor versus the American sensors are more dispersed and indicate that MERIS values are lower in oligotrophic waters and higher in eutrophic waters. Surprisingly, these two discrepancies of opposite sign cancel each other out and lead to a linear fit very close to the identity.

Table 2 gives some statistical parameters of the average chlorophyll-a measured in RSS by SeaWiFS, MODIS and MERIS from December 2002 to March 2003. The dynamical range of all the radiometers is very similar (about $0.04 - 20 \text{ mg m}^{-3}$). It is confirmed that the American sensors have a larger coverage and the European

sensor measures higher chlorophyll-a values (difference of about 30 – 40%). The values below 0.05 mg m^{-3} or over 50 mg m^{-3} are practically absent. Those results agree with the expectation that ocean colors satellite radiometers are accurate within 35% and carry out measurements over the range $0.05 - 50.0 \text{ mg m}^{-3}$ (Werdell et al. 2003).

Table 2. Statistical parameters of the average chlorophyll-a measured in RSS by SeaWiFS, MODIS and ELF-calibrated MERIS from December 2002 to March 2003.

	SeaWiFS	MODIS	MERIS
Maximum	23 mg m^{-3}	21 mg m^{-3}	15 mg m^{-3}
Minimum	$4.1 \times 10^{-2} \text{ mg m}^{-3}$	$4.4 \times 10^{-2} \text{ mg m}^{-3}$	$3.6 \times 10^{-2} \text{ mg m}^{-3}$
Average	0.32 mg m^{-3}	0.28 mg m^{-3}	0.41 mg m^{-3}
Measured concentrations	230004 (76%)*	214961 (71%)*	160143 (53%)*
Concentrations $< 0.05 \text{ mg m}^{-3}$	21 (0.01%)	2 (< 0.01%)	147 (0.09%)
Concentrations $> 50 \text{ mg m}^{-3}$	0 (0%)	0 (0%)	0 (0%)
Mean of differences	SeaWiFS-MODIS: 2% SeaWiFS-MERIS: -32% MODIS-MERIS: -43%		

* Relative to the total number of pixels (302400). Permanent ice and land cover 4% and 8% of the zone, respectively.

If this research is compared to a study carried out with data downloaded in Spring 2004 on the match up between SeaWiFS and MODIS (Barbini et al. 2005) in RSS from January to March 2003, it can be observed that the linear fit of the scatter plot is now closer to the identity and the average difference between SeaWiFS and MODIS chlorophyll-a values passed from 35% to 2%. This is not surprising, because at that time MODIS measurements

were provisional, and demonstrate the potential of data reprocessing.

4. Conclusions

The chlorophyll-a maps retrieved by SeaWiFS and MODIS show a very good agreement in RSS from December 2002 to March 2003. This result demonstrate that the reprocessing of MODIS improved the quality of its data (a similar study carried out in RSS nearly in the same period, but with data downloaded in Spring 2004, gave a discrepancy of about 35%). That agreement could have even been better if SeaWiFS and MODIS were regionally calibrated.

MERIS has a more complex behavior with respect to SeaWiFS and MODIS. If the quality flag is not taken into account it has a larger coverage but its values are substantially higher. On the contrary, retaining only the best pixels, it has a smaller coverage while its values stay higher (about 100% in RSS). Nevertheless, the comparison between ELF and satellite radiometers indicates that the European sensor performs better than the American sensors in coastal zones. This suggests that MERIS, if properly calibrated, has a high potential, especially in coastal zones. In fact, once calibrated with ELF, the discrepancy between the European sensor and the American sensors reduces to about 35%, i.e. below the error expected in chlorophyll-a retrieval by ocean color satellite radiometers.

The lesson learned from this exercise is twofold. From one hand, it is confirmed that we still need instruments measuring chlorophyll-a in close proximity to the sea, especially if, like our instrument, they are able to operate H24. From the other hand, it is demonstrated how useful can be a regional calibration of satellite radiometers bio-optical algorithms in order to obtain an accurate estimate of oceanic phytoplankton.

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