MERIS VALIDATION IN THE NORTH WEST MEDITERRANEAN AND THE MASCARENE RIDGE AREA OF THE INDIANOCEAN

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INTRODUCTION

A time series of measurements of phytoplankton pigments and above water reflectance at times of MERIS overflights were made at a site in the north-west Mediterranean, close to the Blanes canyon, for the MERIS validation period (6 months after the first images were available, May to October 2002. Additionally measurements of phytoplankton pigments and above water reflectance were made at times of MERIS overflights during a cruise in the Mascarene Ridge region of the Indian Ocean in June and July 2002. This paper evaluates the number of good quality match-ups of MERIS and *in situ* data for the 2 areas. Secondly it evaluates the accuracy of the chlorophyll data for the 2 sites by comparison with *in situ* data. Thirdly the MERIS reflectance data are compared with above water reflectance measured *in situ* with Satlantic sensors. One of the reasons for choosing the Blanes canyon area was that it was possible there to obtain a time series of measurements for the entire MERIS validation period. An additional opportunity of working in the Indian Ocean arose as part of the cruise work plan was devoted to MERIS and AATSR validation.

STUDY SITES

NW Mediterranean

The continental shelf off Blanes is relatively wide for the Mediterranean, with the 1000 m isobath extending to about 35 Km offshore. The Blanes canyon is a major feature in the bottom morphology bringing the 200-m isobath to only about 4 miles from the shoreline. The canyon bottom drops to more than 2000 m within about 15 Km and bisects the Catalan current flowing SW all along the NW Mediterranean coast. During periods of high precipitation in winter there may be some influence of inorganic and biogenic particles, but during spring and summer the particles are generally phytoplankton [1]. The study took place during overpasses of the ENVISAT satellite from 1st May to 30th October, from the 8 m long vessel *Itxasbide*. Fig.1 shows the study area.

Mascarene Ridge

The study of the Mascarene Ridge (MR) (between 5 and 21° S, 55 to 65°W) took place between 1st June and 11th July 2002, on RRS Charles Darwin. The cruise track (Fig.1) covered the full extent of the MR, firstly proceeding south from the Seychelles down the eastern side of the MR, surveying the deep water (up to 3000m), and then traversing northwards from Mauritius to the Seychelles sampling the shallower waters (shallowest depth was 200m) over the sills along the Ridge system, and finally turning to the south towards Mauritius again in the deeper waters off the west of the MR.

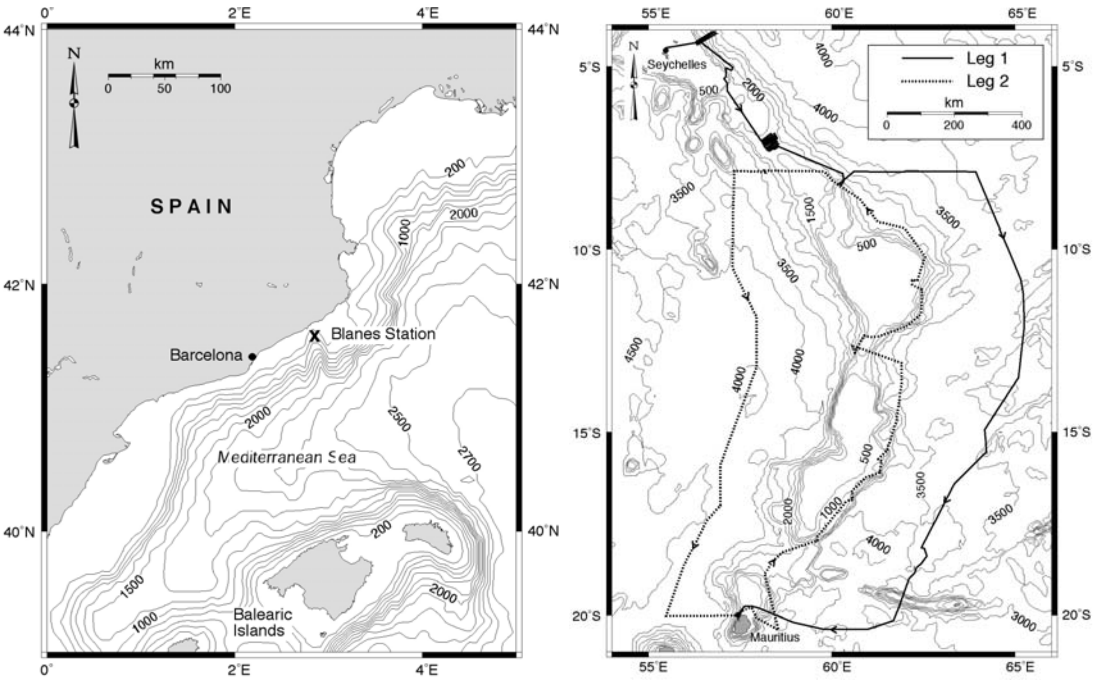

Fig.1. Map of the study areas. Left: NW Mediterranean, showing the Blanes station position; right: the cruise track of RRS Darwin in the vicinity of the Mascarene Ridge on CD 141.

METHODS

Western Mediterranean

A time series of measurements were made during ENVISAT overpasses (approximately every 3 days) at a site 4 miles off the coast of Blanes, Spain (49 39.15°N, 2 52.67°E). A list of the days on which measurements were made is shown in Table 1. Measurements of surface downwelling irradiance were made with a Satlantic sensor (OCR507) mounted on a mast at the highest point of the vessel and powered by a 12V battery). Profiles to 60m of downwelling irradiance and upwelling radiance were made using a Satlantic profiling instrument (OCP023) bearing downwelling irradiance (OCI200), upwelling radiance (OCR200) and pressure sensors mounted on a small rig and operated via a 12V battery. Table 2 shows the wavelengths and the bandwidths of the sensors. Measurements were made with the sun on the starboard side to prevent ship shadow affecting the measurements. Within 30 minutes prior to the light profiles water sampling was carried out with Niskin bottles at various depths down to 200 m after a profile was carried out to this depth with a Seabird 19+ self-recording CTD fitted with a WETLABS flow-through fluorometer. Table 4 shows the times of the ENVISAT overflights and the time of sampling from the vessel. Secchi disk readings and meteorological observations were also made.

The light sensors were calibrated at Satlantic, Canada, immediately prior to the fieldwork activities, and calibrated at Plymouth Marine Laboratory in December 2002, prior to be sent back to Satlantic for post-cruise evaluation and calibration. The calibration at PML in December 2002 was used in the study of the inter-calibration of instruments for the MAVT.

Water samples were collected at 1, 5, 10, 25, 50, 75, 100, 125, 160 and 185 m depths for nutrients (nitrate, nitrite, phosphate and silicic acid), pigment and phytoplankton taxonomic analysis. Chlorophyll pigments were analysed at the CEAB by the spectrophotometric method and Chlorophyll a, b and c were computed following [2]. For this purpose, 3 L of water were filtered from all samples through 45 mm GF/F Whatman filters. Pigment analyses from 1, 5 and 50 m depth samples using high performance liquid chromatography (HPLC) were carried out at SOC following [3]. Duplicate samples of 0.75 L were filtered through 25 mm GF/F Whatman filters. The filters were stored at -70°C until the analyses were carried out. The HPLC was calibrated using pigment standards from DHI, Denmark. The following pigments were quantified: chl c3, chl c2, peridinin, 19'butanoyloxyfucoxanthin, fucoxanthin, 19'hexanoyloxyfucoxanthin, alloxanthin, diadinoxanthin, violaxanthin, zeaxanthin, DV-chl b, chl b, DV-chl a, chl a, b-carotene, and phaeopigments.

Table 1.Dates of overpasses and cruises at the Blanes site. NI: no image received (NI* received only for 3rd processing stage). The dates in bold are the ones that were finally used as match-up data for the third (August 2003) processing stage.

Date	Data	Data quality				
	Image	In situ	Cloud	Glint	Dust	Cont.aer.
20020517	y		y			
20020524	Y		n	n	y	n
20020527	NI					
20020530	y		y	y	y	n
20020612	**y**	**n**	**n**	**y**	**n**	**n**
20020618	NI	y				
20020621	y	y	y			
20020628	NI	y				
20020701	y	y	y	y	y	
20020704	y	y	y			
20020710	NI					
20020717	y	y	n	n	n	n
20020723	y	y	n	y		y
20020802	y	y	y	n		
20020805	NI	y				
20020808	a	y				
20020814	y	y	y	y		y
20020818	NI	y				
20020821	**y**	**y**	**n**	**n**	**n**	**n**
20020827	y	y	y			
20020830	y	y	n	y		y
20020906	NI*					
20020909	NI	y				
20020912	y	y	y			
20020915	NI	y				
20020918	y	y	(y)	y	y	
20020925	**y**	**y**	**n**	**n**	**n**	**n**
20021001	a	y				
20021004	NI					
20021011	NI					
20021014	**y**	**y**	**n**	**n**	**n**	**n**
20021017	NI					
20021023	NI					
20021030	NI					

Table 2. Wavelength positions and bandwidth of Satlantic sensors used during Blanes and Indian Ocean cruises

MERIS	Satlantic Spain OCP023 (Profiler) OCR-507 (Surface Ed)		Satlantic Indian Ocean OCP02 (Profiler) Di7055 (Surface Ed)	
channel	wavelength	width	wavelength	width
1	412.3	10	412.4	10
2	442.3	10	442.6	10
3	489.7	10	490.9	10
4	509.6	10	509.9	10
5	559.5	10	560.1	10
6	619.4	10	620.7	10
7	664.3	10	665.3	10

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Table 3. Dates of overpasses and positions for the Indian Ocean cruise. NI: no image received. The dates in bold are the ones that were used as match-up data (satellite image processing was August 2003).

Date	Image	Lat	Lon
20020406	NI	-5° 14.04'	-57° 17.16'
20020506	*NI	-7° 9.25'	-58° 5.55'
20020608	*NI	-7° 59.99'	-61° 27.91'
20020609	*NI	-7° 59.91'	-63° 21.99'
20020615	**y***	**-16° 29.02'**	**-63° 26.95'**
20020618	**y**	**-19° 45.94'**	**-61° 55.15'**
20020624	**y**	**-18° 36.83'**	**58° 25.13'**
20020627	**y**	**-14° 12.78'**	**-61° 56.17'**
20020701	NI	-10° 45.29	-62° 30.38'
20020703	NI	-8° 01.87'	-58° 10.56'

Table 4 Overpass and *in situ* sampling times for Blanes station (left) and Indian Ocean cruise CD141 (right).

Sampling/ overflight times (GMT) 2002 Spain				Sampling/ overflight times (GMT) 2002 Indian Ocean S			
Date	Jday	overpass	Satlantic	Date	Jday	overpass	Satlantic
12/6/02	163	10:41	10:05	15/6/02	166	05:30	05:23
28/6/02	179	10:07	08:45	18/6/02	169	0607	07:18
21/8/02	233	10:10	09:17	24/6/02	175	0550	0720
25/9/02	268	10:16	10:02	27/6/02	178	0623	0649
14/10/02	287	10:13	09:27				

Mascarene Ridge

Measurements were made at the time of ENVISAT overpasses (approximately every 3 days) on cloud free days. A downwelling irradiance sensor was interfaced with a data acquisition module at Satlantic (MVD500) and mounted on the foremast. Profiles of downwelling irradiance and upwelling radiance to 60m were made using a small rig deployed from a crane using a slip ring winch on the aft deck from the starboard side. Measurements were made of downwelling irradiance (OCI200) and upwelling radiance (OCR200), with the sun on the starboard side to minimise the effect of ship shadow on the measurements. Table 2 shows the wavelengths and bandwidths of the Satlantic sensors. Dates of the match-ups and the positions are shown in Table 3. Table 4 shows the sampling and light profile time. The same calibration procedures were carried out as for the NW Mediterranean.

A profiling CTD (SeaBird) and fluorometer (Chelsea Instruments, Mark III) were deployed immediately before the Satlantic profiles. Water samples were taken for pigment and phytoplankton taxonomic analysis on the CTD upcast using the Niskin bottles mounted on the rosette on the CTD frame. These were taken during every CTD, which sampled the top 200 m in detail. 6 samples were taken in the top 200m, filtered and stored in liquid nitrogen. The water was filtered using GF/F Whatman filter papers, taking 2 replicated for each depth, and then stored in liquid nitrogen. The pigments were identified and quantified by high performance liquid chromatography (HPLC) at SOC nutrients following the method described above for the NW Mediterranean. Water samples were also taken for nutrients.

Intercomparison of Chlorophyll pigments

The inter-comparison of pigments measured by the MAVT laboratories was carried out by both SOC, for chlorophyll-a measured by HPLC, and by CEAB, for chlorophyll-a measured by the spectrophotometric method. This was carried out on 2 occasions: August and November 2002. The results of the two exercises are contained in the paper on inter-comparison of chlorophyll-a [4].

The scatter in the results of the HPLC inter-comparison was large and was attributed to differences in methods and laboratory techniques. About half the participants' measurements were greater than the 20% of the median value of all the laboratories' measurements, which were the criteria adopted by the MAVT. It would have been beneficial to take this matter further, for example, by organising a workshop on HPLC techniques for the HPLC operators in the MAVT but time and funds made this impractical (see Discussion).

Generally the scatter in the spectrophotometric inter-comparison was significantly smaller, with the majority of participants measurements falling within the 20% acceptable error limits. Particularly the measurements carried out by Zoila Velasquez at CEAB in this study were within 10% of the median of the samples, and so were acceptable for the validation for the Blanes site.

Samples measured by HPLC at SOC were 50% lower than the median value obtained in the MAVT inter-comparison. Therefore for the validation of MERIS chlorophyll for Blanes, only the spectrophotometric measurements were used. For the Indian Ocean, in order to have an estimate of the chlorophyll concentrations, a statistical relationship between the chlorophyll-a measured by the 2 methods was determined from the Spanish data set. For the Spanish study the 2 methods were used in parallel throughout and the resulting data were used to convert the HPLC measurements to predicted chlorophyll-a values for the Indian Ocean data. Figure 2 shows the HPLC and spectrophotometric replicates from the Spanish data set, which was the basis of the statistical analysis. In addition, as replicates were taken of both sets of measurements, these were averaged, and it is this that is shown as HPLC chla in Fig. 2. The statistical relationship between the datasets is also shown (r^2 value is 39%).

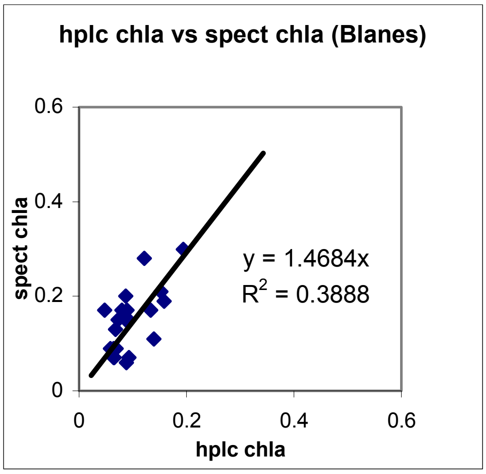


Fig. 2. Chlorophyll-a measured by HPLC and spectrophotometer for the Blanes study.

RESULTS

Analysis of MERIS data for processing stages December 2002 and March 2003

NW Mediterranean

34 sets of measurements coinciding with MERIS overflights were planned, although because of bad weather causing last minute cancellations, only 28 cruises were carried out and these are shown in Table 1, along with the MERIS data quality flag indicators. For the MERIS data processing stage in December 2002, 14 images were not received; some of these had not been sent to ESA from the receiving station (Kiruna), and some were not sent to SOC from ESA; 6 images did not have supporting Satlantic data, due to a breakdown of the Lu sensor on the profiler in July 2002. For the processing stage August 2003, a number of awaited images were received form ESA.

Data quality procedure was to view the Level 1 images using ENVIVIEW and to make an overall assessment of the cloud cover. Then VISAT was used to select the match-up location from the Level 2 chlor-a images. A summary of the data quality from the flags for the match-up location is shown in Table 1. The columns marked 'dust' and continental aerosol are the two aerosol flags. Wind speeds were in all cases less than 2 ms^{-1}. The SMILE correction had been performed by ESA on all images to up to 14th October. Level 2 images were examined for camera artefacts, and in the subsequent processing camera artefacts were corrected. The quality of the images is summarised in Table 1. Only the dates with 'n' in the cloud, glint, dust and continental aerosol columns are entirely 'error flag free'. However, although at this stage the analysis was not complete, so all the possible match-ups were used for the initial chlorophyll-a comparison.

For the comparison of satellite and *in situ* chlorophyll, firstly the Level 2 chlorophyll-a value was selected for the closest pixel to the ships position; secondly the surrounding 9 pixels were sampled and the average and standard deviation were calculated (Table 1). The chlorophyll a data is the average of the measurements in the mean optical depth (25m), and the standard deviation represents at least 6 measurements (3 depths in the top 25m, and 2 replicates for each depth.

Indian Ocean
There were 15 possible match-ups with ENVISAT, of which 4 were received from ESA. The cruise was carried out during a period where there was some patchy cloud, and very few absolutely clear days. The same procedure for evaluation of data quality was carried out as for the images of the NW Mediterranean.

Analysis of MERIS data for processing stage August 2003

Following the August 2003 processing of the MERIS data it was found that many of the Blanes images had negative radiances, which is thought to be due to the incorrect atmospheric correction because of the close proximity to vegetated land cover (affecting the near infrared signal). For this reason only images in bold in Table 1 were used for the validation, on the request of the MERIS team at ESTEC. The reason for this is the subject of further investigation. The table below shows the final data set used with MERIS data processed in August 2003.

Table 5. Final match-up table for 2002. xp is predicted chlorophyll from the algorithm relating spectrophotometric and HPLC measurements for the Spanish data set, as the HPLC data could not be directly used (see METHODS and Indian Ocean Chlorophyll sections in this paper).

Spain	Reflectance		
Date	MERIS	Satlantic	in situ chl
12/06/2002	x	x	
21/08/2002	x	x	x
25/09/2002	x	x	x
14/10/2002	x	x	x
Indian Ocean			
15/06/2002	x	x	xp
18/06/2002	x	x	xp
24/06/2002	x	x	xp
27/06/2002	x	x	xp

MERIS chlorophyll

A comparison was made between the MERIS and *in situ* chlorophyll for the March 2003 processing stage and is shown in Fig. 3. The chlorophyll values were all quite low (less than 0.4 mg m^{-m3}). As this was not the final stage of processing for the validation, the statistics are not relevant, and it is clear that some of the errors shown here are unacceptably large. Indeed the diagram indicates that the standard deviation of the surrounding pixels is larger than any trend in the data. Figure 4, however shows the data from the August 2003 processing stage, where much fewer images were acceptable in terms of quality because of artefacts in the MERIS reflectance, which were unusually low or negative radiances, discussed earlier. This comparison shows that MERIS overestimates chlorophyll at the Blanes site by almost a factor of 1.8.

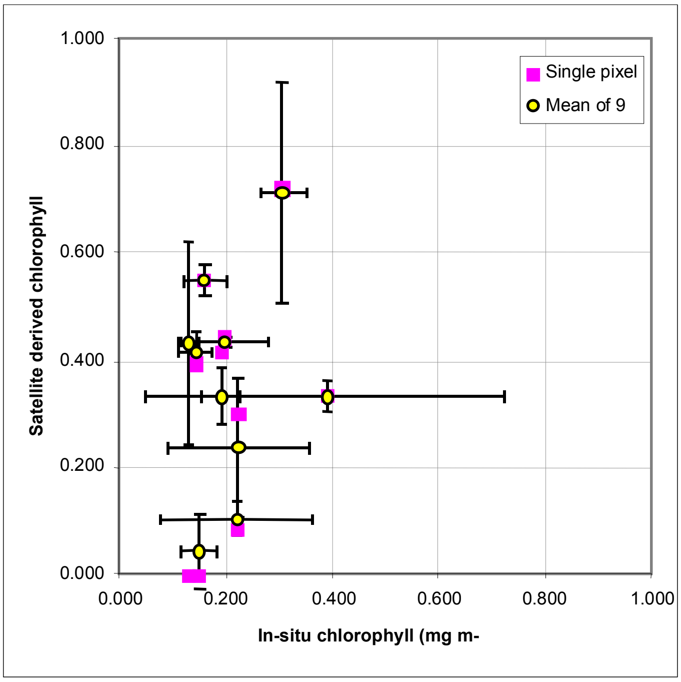


Fig.3. MERIS chl-a Vs *in situ* chlorophyll-a Marc 2003 processing). The horizontal error bars represent the sample standard deviation, taken from the surface to 25m. The MERIS chl-a data is presented as a yellow symbol for single pixels, a pink symbol for the mean of 9 pixels and the vertical error bars represent the standard deviation.

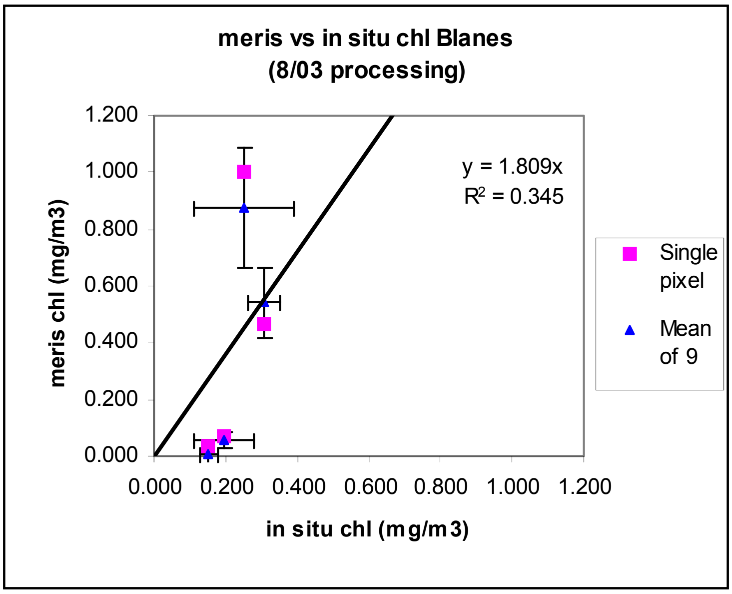


Figure 4 Comparisons of chl from MERIS (August 2003 processing) and *in situ* chl.

Indian Ocean chlorophyll

The pigments measured in the Indian Ocean were by HPLC only and the MAVT inter-comparison has shown that the measurements made at SOC were systematically low by at least 40%. Therefore an algorithm was calculated by comparing the two sets of samples measured for the Spanish data set, by HPLC and spectrophotometry (see methods above). Therefore we do now have values for *in situ* chlorophyll-a for the Indian Ocean match-ups, but they are predicted.

The comparison of MERIS chlorophyll a and *in situ* chlorophyll-a, is shown in Fig. 5, and the correlation is 0.86, with a coefficient of determination of 74%. MERIS gives a chlorophyll-a value 30% higher than the *in situ* values.

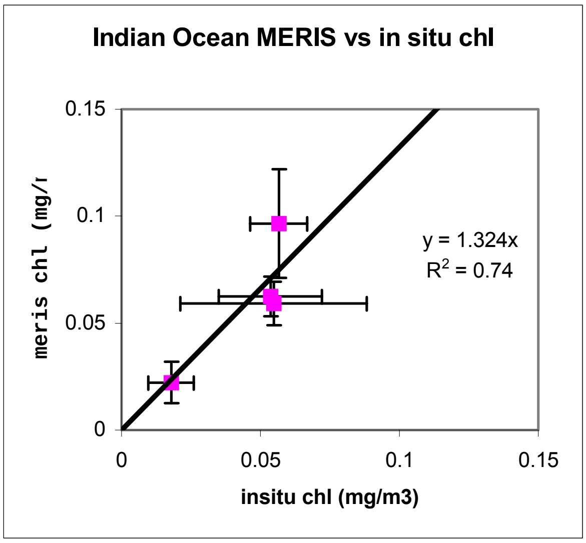


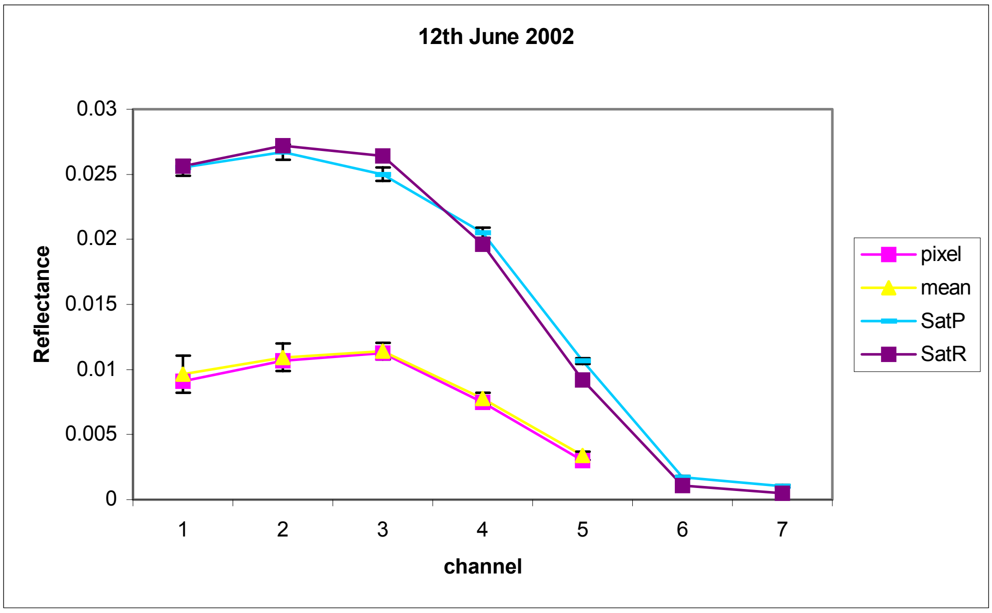
Figure 5. Comparison of MERIS and *in situ* chlorophyll-a for Indian Ocean cruise.

Comparisons of MERIS and *in situ* reflectance for the August 2003 processing stage.

NW Mediterranean

Comparison has been made of a MERIS (Level 2) reflectance spectrum with the above water reflectance spectrum from the Satlantic data, profiles of downwelling irradiance and upwelling radiance and surface irradiance. Initially reflectance was calculated using above surface values of Lu and Ed, which were obtained by firstly extrapolating the profiles to the surface, and then calculating the transmission through the surface [5] and [6]. This spectrum is shown in as SatP in Figure 6, where MERIS reflectance is also shown for both the Blanes site and the Indian Ocean. As there was some significant departure from the MERIS reflectance, *in situ* reflectance was recalculated, this time using the surface Ed, from the mast sensor. This is shown as SatR in the plots. This value is in close agreement with SatP for some of the match-up days but there is a seasonal effect, where the difference between SatP and SatR increases after midsummer.

However, despite calculating reflectance both ways, there is still a significant difference between MERIS and Satlantic reflectance for the Blanes station. This may be explained by the fact that the aerosol correction is too intense for this site, and so values of MERIS reflectance are too low.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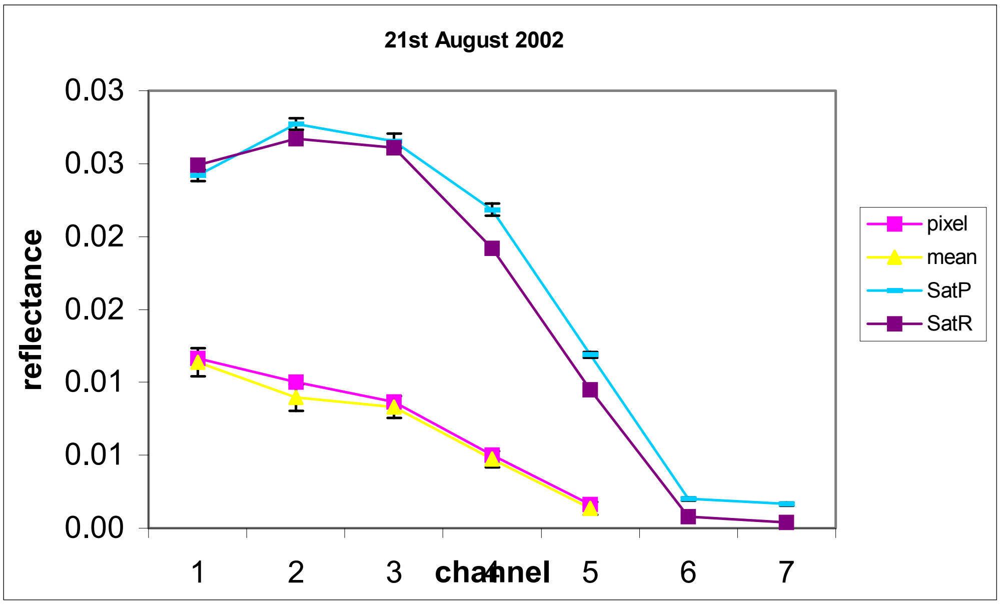
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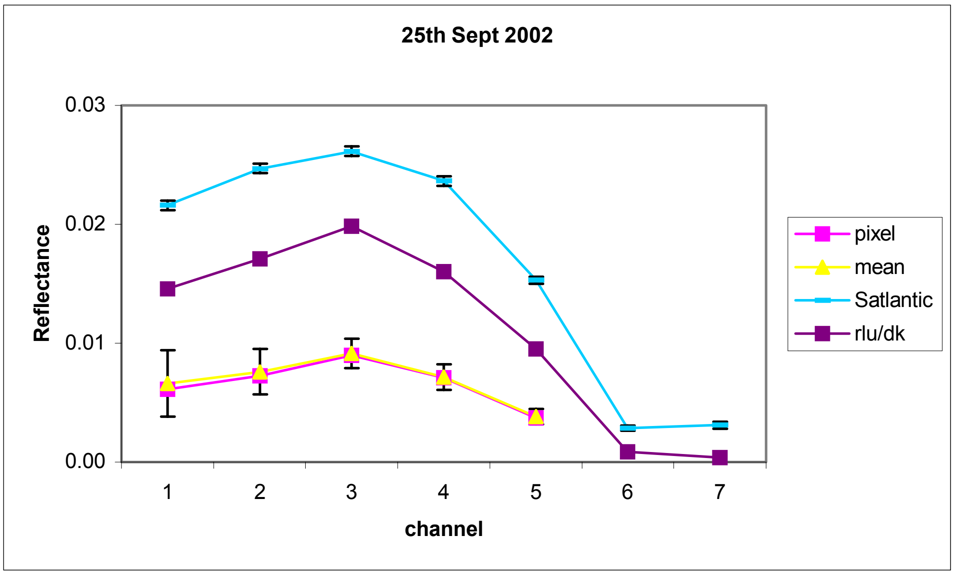
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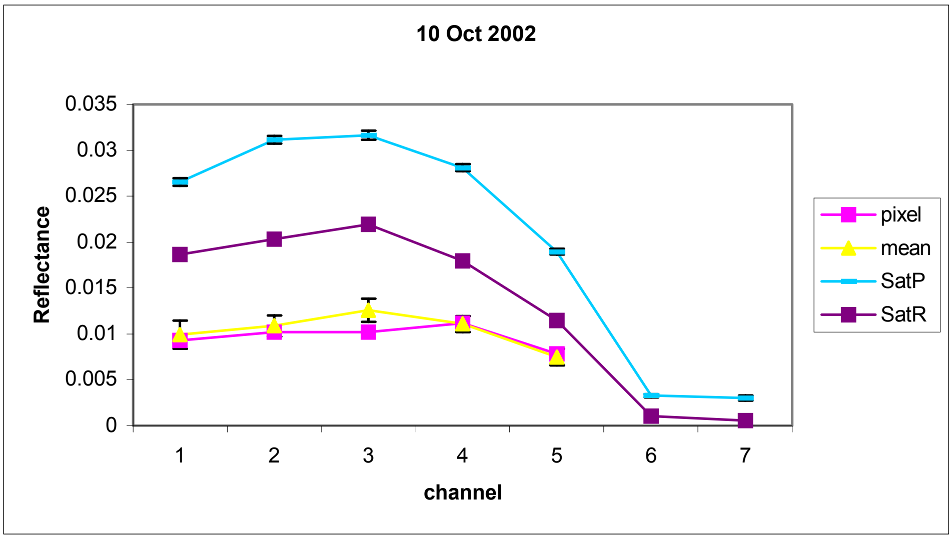
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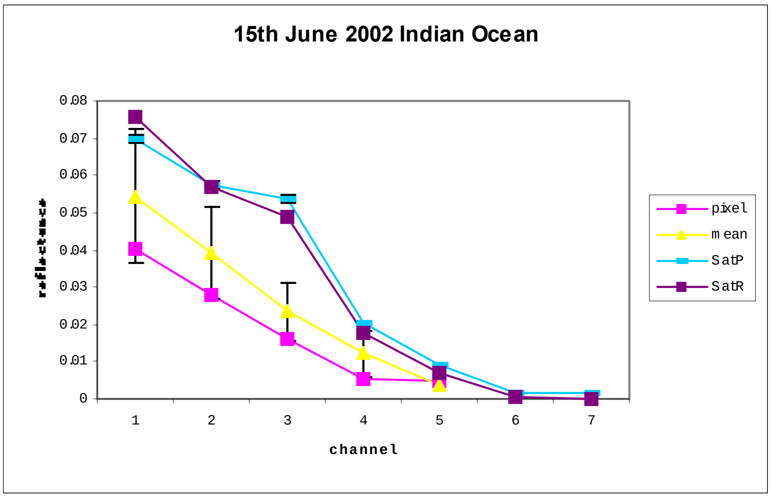
Figure 6. Comparisons between MERIS and *in situ* reflectance (August 2003 processing stage) for the 4 match-ups for the Blanes site. The MERIS data central pixel for the Blanes site is shown (in pink) and the mean of this and the 8 surrounding pixels is also shown. Error bars for MERIS are ± 1 standard deviation from the mean of the 9 pixels centred on the Blanes station. Error bars for Satlantic (SatP) are ± 1 standard deviation from the mean of the reflectance of the upward and downward cast of the Satlantic profile. The errors for SatR are not shown, but are of the same order of magnitude or less than for SatP.

Indian Ocean

A similar approach was taken for the images from the Indian Ocean, using only the data processed in August 2003. 2 examples are shown in Fig.7, where reflectance from Satlantic is calculated in the same ways as discussed earlier, from Ed and Lu from profiled data (SatP) and from surface Ed and Lu (SatR). There is little difference in these 2 approaches but there is a difference between either of the spectra and the MERIS spectra. Two extremes of MERIS data were used, one with high variability in the pixels surrounding the central location (June 15 2002) and one with very little (June 24th).



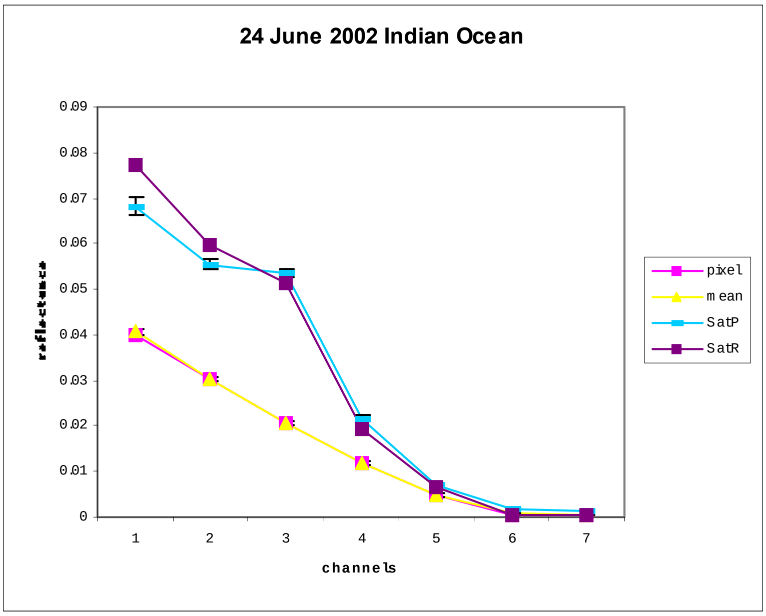


Figure 7. Comparisons between MERIS and *in situ* reflectance (August 2003 processing stage) for 2 examples of data from the Indian Ocean cruise. The MERIS data central pixel for each position (in pink) and the mean of this (yellow) and the 8 surrounding pixels is also shown. Error bars for MERIS are ± 1 standard deviation from the mean of the 9 pixels centred on each station. Error bars for Satlantic (SatP) are ± 1 standard deviation from the mean of the reflectance

of the upward and downward cast of the Satlantic profile. The errors for SatR are not shown, but are of the same order of magnitude or less than for SatP.

DISCUSSION

Two validation campaigns were carried out in 2002 in the NW Mediterranean and in the Mascarene Ridge area of the Indian Ocean, which were simultaneous. A large, good quality data set of *in situ* pigment and optical data were obtained, which were taken at times of the ENVISAT satellite overpass. However, when the image data and the *in situ* data were compared there were many reasons for rejecting the match-ups, so after a total of a potential of approximately 50, only 8 match-ups were obtained for the 2 areas.

For the NW Mediterranean, there was contamination by cloud, glint, aerosols, and some loss of *in situ* data due to bad weather and the temporary breakdown of a light sensor. However the final (August 2003) processing stage caused a number of images which had been accepted previously to be struck from the list of match-ups. This was because this processing procedure resulted in negative radiances calculated at this site. This may be because the site was too close to highly vegetated land, which has been referred to as an 'environmental' effect on the measured radiance in the area.

For the Mascarene Ridge area of the Indian Ocean, this was a cruise that had originally been planned for May, but was postponed. By June the weather was poorer and so there was more patchy cloud cover than was expected in May. For this reason some of the satellite data were not acceptable.

The MAVT inter-comparison for chlorophyll-a was an important part of the validation but it revealed some unacceptable differences in measurement methods in different laboratories. For the spectrophotometric analysis of chlorophyll-a the data used in this study, measured at CEAB, were all within the accuracy criteria of the MAVT, and so the methodology was acceptable for the MERIS and *in situ* match-ups in the NW Mediterranean study. However the HPLC pigment measurements made at SOC were systematically too low by about 50%, and so could not be used for the validation. In the NW Mediterranean study replicates were taken to measure chlorophyll-a by both spectrophotometry and HPLC and so this data set was used to convert the Indian Ocean HPLC data to a predicted measure of chloropyll-a.

The comparison of chlorophyll-a from MERIS and *in situ* in the NW Mediterranean gave an overestimation by MERIS by a factor of 1.8, but with a coefficient of determination of only 34%. This may be partly accounted for by the 'environmental' effect on radiance from MERIS at this location. Comparisons with other sites with proximal coastal vegetation may clarify the importance of this effect. For the Indian Ocean, the comparison of MERIS and *in situ* (predicted) chlorophyll-a showed an overestimation by MERIS of 30%, with a coefficient of determination of 74%.

Comparisons of *in situ* above water reflectance and MERIS reflectance in the NW Mediterranean show some significant differences. Above water reflectance was initially calculated by extrapolating profiles of Ed and Lu to above the surface, and calculating reflectance. But after noting the differences between this and MERIS reflectance, above water reflectance was calculated using the above surface (masthead) Ed along with above-surface extrapolated Lu, as described in [5] and [6]. The second method showed a significant reduction in the difference from MERIS but only in the months of September and October, with little difference in June and August. It is possible that the problem of negative radiances at this site was not entirely solved for the images used, and so MERIS reflectance is artificially low. For the reflectance measured *in situ* in the Indian Ocean, there are differences from MERIS reflectance, particularly at shorter wavelengths.

ACKNOWLEDGEMENTS

The authors would like to thank all those who participated in the fieldwork at CEAB, Spain and on CD141. The authors also thank Nixon Bahamon and Miguel Angel Ahumada at the CEAB and Lisa Redbourn-Marsh, Christina Peckett, Val Byfield and Chris Green at Southampton Oceanography Centre for their work in satellite data and *in situ* data acquisition and processing. The authors would like to thank Kate Davis and Gary Fisher for their technical assistance. Support of the project by the Natural Environment Research Council by the use of RRS Charles Darwin is gratefully acknowledged, as is the support of this project by ESA.

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