INT. J. REMOTE SENSING, 10–20 APRIL, 2004,
VOL. 25, NO. 7–8, 1481–1488

SeaWiFS validation in European coastal waters using optical and bio-geochemical measurements

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Abstract. The National Aeronautics & Space Administration (NASA) Sea viewing Wide Field of view Sensor (SeaWiFS) began operational measurement of ocean colour in September 1997. Upgrades to the SeaWiFS data processing system (SeaDAS) have occurred frequently and the effects of these revisions on the remotely sensed estimates of chlorophyll-*a* concentration (chl-*a*) have been significant. Measurements of chl-*a* from research work in the Bay of Biscay and Gulf of Cadiz during 1998–1999 are used to validate the SeaWiFS chl-*a* product generated using the current version of SeaDAS (version 4.1). The validation data cover coastal and offshore waters, including those dominated by inorganic suspended sediment, and an intense dinoflagellate bloom where shipboard chl-*a* measurements exceeded $50\,mg\,m^{-3}$. The standard SeaWiFS chlorophyll algorithm (OC4v4) generally performed well, but significantly over-estimated chl-*a* where inorganic suspended sediment was present. The algorithm is only applicable to chl-*a* values up to $64\,mg\,m^{-3}$, which was less than chl-*a* at the centre of the bloom. A novel algorithm for chl-*a*, which first estimates the inherent optical properties of the water, was applied to the SeaWiFS measurements but failed on over 90% of the pixels, perhaps because SeaWiFS is under-estimating water reflectance at the extreme blue end of the visible spectrum.

1. Introduction

Satellite remote sensing of ocean colour is the only realistic way to measure many fundamental biological ocean properties, notably, near-surface chlorophyll-*a* concentration (chl-*a*), on basin scales. The National Aeronautics & Space Administration (NASA) global ocean colour sensor, the Sea viewing Wide Field of view Sensor (SeaWiFS), was designed to measure chl-*a* in the range $0.01–64\,mg\,m^{-3}$ to within 35% and has been operational since September 1997

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An updated version of a paper originally presented at *Oceans from Space 'Venice 2000' Symposium*, Venice, Italy, 9–13 October 2000.

International Journal of Remote Sensing
ISSN 0143-1161 print/ISSN 1366-5901 online © 2004 Taylor & Francis Ltd
http://www.tandf.co.uk/journals
DOI: 10.1080/01431160310001592481

(Hooker *et al.* 1992). The SeaWiFS Data Analysis System (SeaDAS) converts SeaWiFS raw measurements to chl-*a* values, and continues to undergo frequent revisions which can significantly change the values of chl-*a*. Up-to-date vicarious validation is essential to ensure confidence in the data. In particular, the performance of SeaWiFS at concentrations of chlorophyll-*a* greater than $10\,\mathrm{mg\,m^{-3}}$ has not been well tested to date. This work compares *in situ* measurements of chl-*a* from two European regions with remotely sensed values from SeaWiFS, processed using the current version of SeaDAS, and discusses reasons for the differences.

2. Methodology

2.1. *Shipboard measurements*

Near-surface chlorophyll-*a* concentration was measured during two European measurement campaigns in 1998–1999: (1) the Plagia cruises in the Bay of Biscay near the Gironde Estuary (Froidefond *et al.* 2001); and (2) a study looking at an intense dinoflagellate bloom in the Gulf of Cadiz off south-west Spain (Caballos *et al.* 2000). See figure 1 for station locations. Water samples from a depth of ca 3 m

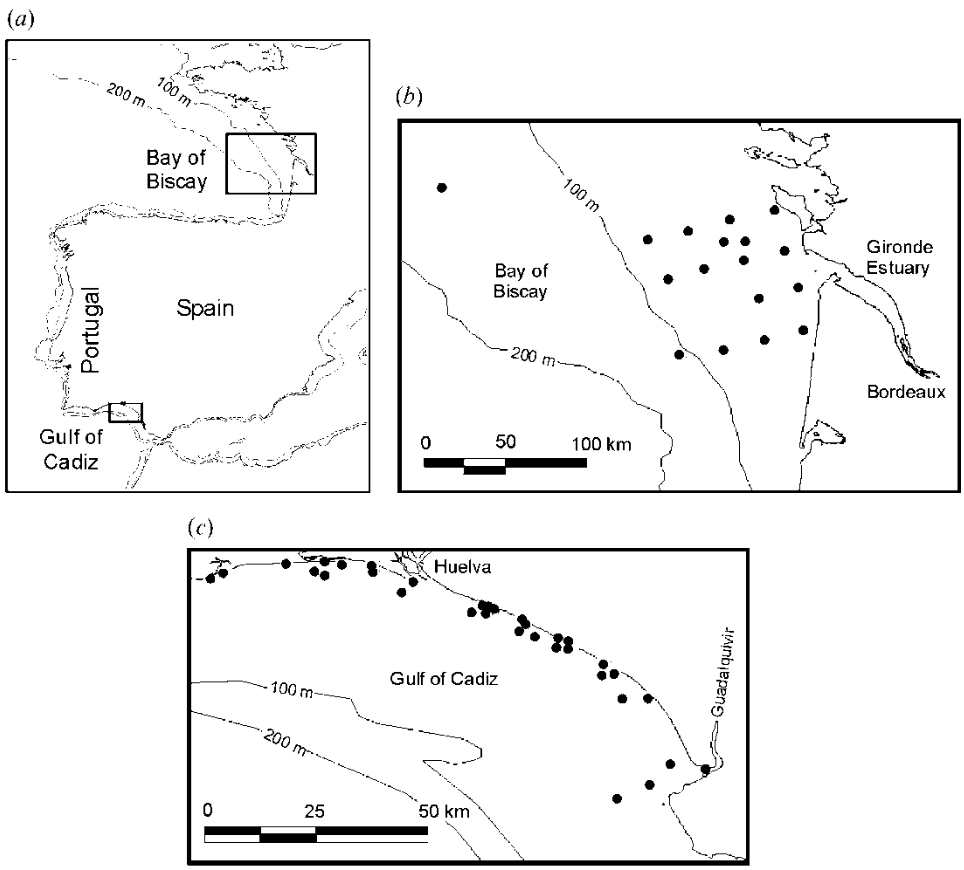

Figure 1. Stations sampled during this validation study. (*a*) Location of the regions studied; (*b*) stations visited during the series of Plagia research voyages in the Bay of Biscay; (*c*) stations visited in the Gulf of Cadiz region.

were analysed for phytoplankton pigment concentration by a combination of high performance liquid chromatography (HPLC), fluorometric techniques (Turner Designs Fluorometer) and spectrophotometry (Kontron UVICON 941 Spectrophotometer) after extraction in 90% acetone. The analysis was either shipboard immediately after water collection, or at the institute laboratory within 4 h of sampling. The water samples were analysed for total suspended particulate matter concentration (SPM, $>0.4\,\mu m$ size fraction) by differential weighing of glass fibre filters.

2.2. *Remotely sensed measurements by SeaWiFS*

SeaWiFS top-of-atmosphere (TOA) data (Level 1a) were processed to the Level 2 chlorophyll-*a* concentration product using SeaDAS 4.1, which was current at the time of writing (Barnes *et al.* 2001, Eplee *et al.* 2001). The ultimate accuracy of the SeaWiFS chl-*a* product relies on both the quality of the measurements of ocean colour (strictly, a spectrum of normalized water-leaving radiance, L_{wn}, Gordon *et al.* 1988) and on the performance of the algorithm used to estimate chl-*a* from ocean colour.

SeaDAS 4.1 calibrates SeaWiFS measurements of TOA spectral radiance using pre-launch data combined with direct and vicarious calibration updates (Barnes *et al.* 2001, Eplee *et al.* 2001). SeaDAS 4.1 calculates ocean colour from TOA measurements using the dark-pixel atmospheric correction method (Gordon and Wang 1994, Wang 2000). This method is applicable only to waters with low amounts of particulate material where there is negligible water reflectance in the near-infrared (NIR). As some of our *in situ* data were from turbid coastal waters, SeaDAS version 4.1 was amended to include a 'bright pixel' atmospheric correction algorithm (Moore *et al.* 1999, Lavender and Groom 1999). This algorithm extends the atmospheric correction method to highly scattering environments where the assumption of zero L_{wn} in the NIR fails.

SeaDAS 4.1 applies the SeaWiFS Ocean Colour 4 version 4 algorithm (OC4v4: O'Reilly *et al.* 1998, 2000) to the L_{wn} spectrum to estimate chlorophyll-*a* concentration. OC4v4 uses the ratio of the L_{wn} in a blue band (443, 490 or 510 nm) to that in the green band (555 nm) to estimate chl-*a*. The algorithm was based on *in situ* measurements of chl-*a*, the vast majority of which lay between 0.08 and $3\,mg\,m^{-3}$. Ocean colour is influenced by all coloured material in the water, principally phytoplankton and associated detritus, inorganic suspended particulate material (SPM) and coloured dissolved organic material (CDOM) from land run-off. The OC4v4 algorithm is applicable only to those areas where the ocean colour is determined exclusively by material of phytoplankton origin (known as Case 1 waters). The approach is effective even though the blue band does not lie within the main region of absorption by chlorophyll-*a* (400–470 nm) because accessory pigments, mostly carotenoids, absorb throughout the blue part of the spectrum and these co-exist and co-vary with chlorophyll-*a* over most ocean provinces. A two-band ratio algorithm such as OC4v4 will fail where the phytoplankton pigment assemblage is unusual, or where ocean colour is influenced predominantly by SPM and/or CDOM (so-called Case 2 waters), because it cannot distinguish the optical characteristics of carotenoids, CDOM or SPM from those of chl-*a*. A model based on the inherent optical properties (IOP) of the water (absorption and scattering) has been designed to separate the optical properties of different material and provide more accurate estimates of chl-*a* in these conditions (Moore and Aiken

2003). This IOP model was applied to the SeaWiFS measurements of ocean colour for comparison with OC4v4.

2.3. *Comparison methodology*

In situ measurements of chl-*a* were compared to values of chl-*a* extracted from SeaWiFS images to give an end-to-end assessment of the quality of the remotely sensed data. Very few exact match-ups, i.e. *in situ* and remote measurements of chl-*a* concentration at exactly the same location at the same instant of time, are available. At European latitudes there are 1–2 SeaWiFS overpasses of a given location per day and many of these overpasses yield no SeaWiFS data because of cloud cover. In contrast, shipboard measurements of chl-*a* are generally made throughout the day to maximize use of shipboard research time. A balance must be achieved between the amount of spatial and temporal separation between the *in situ* and remote measurements that is deemed acceptable for comparison, and the number of comparisons required for the results to be statistically valid. The method of selecting satellite data will affect the comparison results because bio-optical properties vary on short spatial and temporal scales that may be similar to the separation of the *in situ* and remotely sensed data. For example, internal waves and/or internal tides affect surface phytoplankton abundance at time-scales of <1 day.

This study exclusively used SeaWiFS High Resolution Picture Transmission (HRPT) data at 1 km resolution for comparison. Data were extracted from a 3×3 grid of pixels centred on the location of the *in situ* measurement, assuming that a point measurement of chl-*a* is representative of the average chl-*a* concentration for a $9\,km^2$ area containing the sample. Spatial Fourier analysis of time-series fluorometer data from a moored data-buoy suggest that this assumption is reasonable (Pinkerton 2000). All SeaWiFS data used in the comparison were measured on the same day as the shipboard measurement at between 11:30 and 14:00 h local time, giving a maximum time difference between the *in situ* and remote measurement of <8 h.

3. Results and discussion

The chl-*a* concentration of water sampled during the Plagia cruises in the Bay of Biscay near the outflow of the Gironde estuary was between 0.2 and $4.6\,mg\,m^{-3}$ (mean of $1.2\,mg\,m^{-3}$). The SPM concentration varied between 0.05 and $28.4\,g\,m^{-3}$, with a mean of $2.5\,g\,m^{-3}$, and SPM often dominated the optical properties of the water (Froidefond *et al*. 2001). There were 231 valid comparisons between SeaWiFS and *in situ* data and the comparison results are shown in figure 2 and table 1. Only 13 of the 231 comparison points activated the bright pixel atmospheric correction method, and total suspended matter (TSM) was estimated with good accuracy relative to *in situ* measurements in these cases. The average difference in TSM, expressed as a percentage of the *in situ* measurement, was -34% (i.e. the estimated value was lower than the shipboard measurement on average) and the rms. difference (a measure of scatter) was 64%. The OC4v4 chl-*a* product for a typical SeaWiFS image of the Bay of Biscay region (26 May 1999) is shown in figure 3(*a*) and the region where the bright-pixel atmospheric correction method was activated is shown in figure 3(*b*). SeaWiFS over-estimated chl-*a* relative to the *in situ* values by a factor of three, on average. The rms. difference between the *in situ* and remote measurement was over 250%. The over-estimation of chl-*a* by OC4v4 is consistent with the effect of scattering by inorganic material, which increases reflectance across

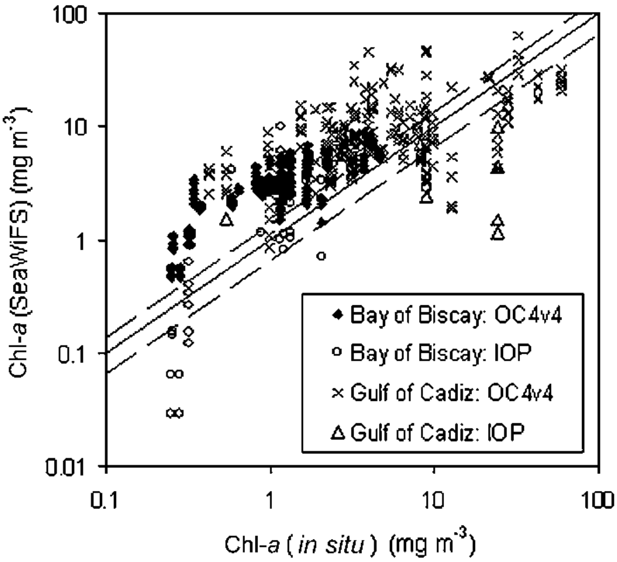

Figure 2. Comparison of *in situ* and satellite-derived values of chlorophyll-*a* concentration (chl-*a*) measured on the series of Plagia research voyages in the Bay of Biscay, and data measured in the Gulf of Cadiz region. The results from the SeaWiFS standard algorithm (OC4v4) and from the inherent optical property model (IOP) are shown. The 1 : 1 line is shown solid and the dashed lines indicate the $\pm 35\%$ error range.

the whole visible spectrum, tends to decrease the blue-green ratio and increase the chl-*a* estimate. The performance of OC4v4 is much better in the 26 comparisons where the waters are likely to be Case 1 (those which have a SeaWiFS chl-*a* value of

Table 1. Differences between SeaWiFS and *in situ* measurements of chlorophyll-*a* concentration (chl-*a*).

			chl-*a* comparison			
Region	Algorithm	Data selected	*n*	Mean difference (%)	Mean ratio	rms. difference (%)
Bay of Biscay	OC4v4	All data	231	+201.2	3.0	253
	OC4v4	chl-*a* (SeaWiFS) $< 1\ \mathrm{mg\,m^{-3}}$	26	+136.6	2.4	154
	IOP	All data	31	+93.4	1.9	228
Gulf of Cadiz	OC4v4	All data	258	+155.0	2.6	274
	OC4v4	Offshore (> 1 km from coast)	141	+106.9	2.1	202
	OC4v4	chl-*a* (*in situ*) $> 5\ \mathrm{mg\,m^{-3}}$	104	+16.8	1.2	121
	IOP	All data	7	−33.0	0.7	99

SeaWiFS data were taken from a grid of 3×3 pixels centred on the *in situ* measurement, from the best image on the day of the *in situ* measurement. The table shows the total number of comparisons (*n*), the mean difference between the SeaWiFS and *in situ* measurements, the mean ratio of SeaWiFS value to the *in situ* value and the rms. of the difference. The differences are expressed as a percentage of the *in situ* measurement. The mean difference and mean ratio indicate bias. The rms. difference measures the scatter in the comparison. See the text for a discussion of the results.

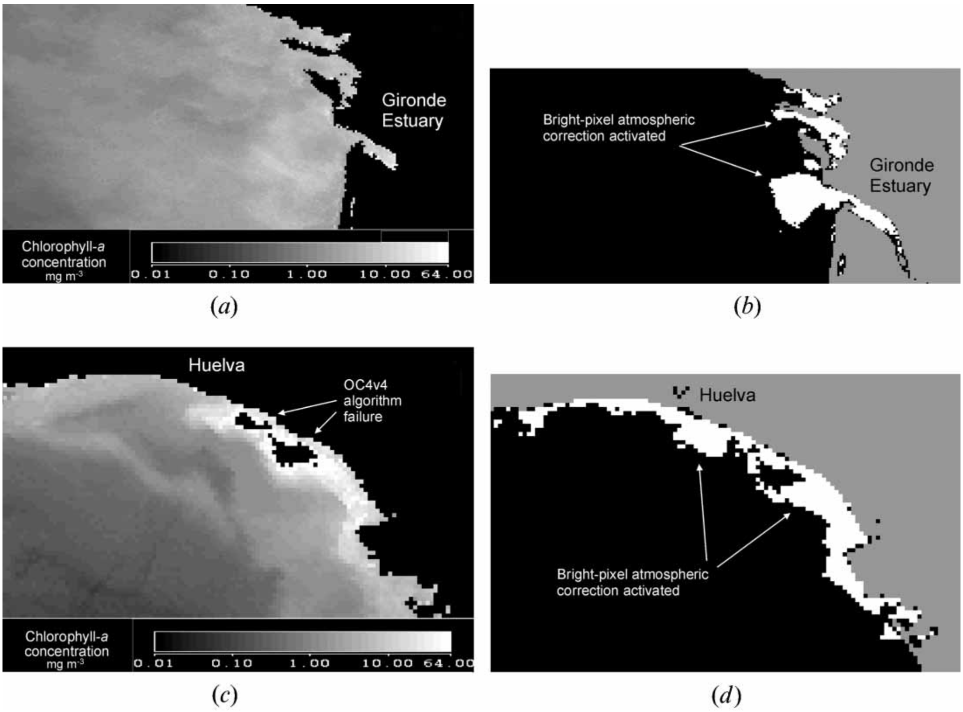

Figure 3. (*a*) SeaWiFS image of chlorophyll-*a* concentration in the Bay of Biscay region, 26 May 1999. (*b*) The same image showing the areas where the bright-pixel atmospheric correction was required. (*c*) SeaWiFS image of chlorophyll-*a* concentration in the Gulf of Cadiz on 2 June 1998. The OC4v4 algorithm failed at the centre of the dinoflagellate bloom. (*d*) The same image of the Gulf of Cadiz showing the areas which required the bright-pixel atmospheric correction modification to SeaDAS 4.1.

$<1\,\mathrm{mg\,m^{-3}}$). The average over-estimate of chl-*a* by SeaWiFS is then 137% and the average rms. difference from *in situ* value is ca. 150%. The amount of over-estimation of chl-*a* by OC4v4 had a weak, positive correlation with SPM concentration measured *in situ* (correlation coefficient of 0.16). The IOP model only gave a result in 31 of the 231 comparisons (13%); the reasons for this are discussed later. The model performed reasonably well in these few comparisons: the bias was +93% and the rms. difference between the model and *in situ* measurements of chl-*a* was 228%.

Chl-*a* values measured on the research voyage in the Gulf of Cadiz varied between 0.4 and $59.2\,\mathrm{mg\,m^{-3}}$ (mean of $8.1\,\mathrm{mg\,m^{-3}}$), the data encompassing measurements made in an intense dinoflagellate bloom, and in the sediment plume at the mouth of the Guadalquivir river. TSM values varied between 8.0 and $47\,\mathrm{g\,m^{-3}}$, with an average of $21.1\,\mathrm{g\,m^{-3}}$. The 258 comparisons between SeaWiFS and shipboard measurements showed that OC4v4 over-estimated chl-*a* on average by a factor of 2.6. The rms. difference was nearly 300%. Many of the *in situ* measurements were taken close to the coast where sensor ringing and the Lambertian NIR reflectance of the land can affect the remote measurement of ocean colour. Considering only those pixels $>1\,\mathrm{km}$ from the coast, the average over-estimation was by a factor of 2.1, and the rms. difference was ca. 200%.

OC4v4 performed well in the intense dinoflagellate bloom. In the 104 comparisons where chl-*a* was greater than $5\,\mathrm{mg\,m^{-3}}$, the average difference between SeaWiFS and the *in situ* measurement of chlorophyll was $+17\%$ and the rms. difference was 121%. The extremely high values of chl-*a* associated with the bloom led to high absorption in the blue part of the spectrum resulting in $L_{wn}(443)$ and $L_{wn}(490)$ being reduced to zero in some cases. $L_{wn}(510)$ was never reduced to zero and OC4v4 estimated chl-*a* up to the limit of $64\,\mathrm{mg\,m^{-3}}$. The OC4v4 chl-*a* product for a SeaWiFS image of the Gulf of Cadiz (2 June 1998) is shown in figure 3(*c*) and the region where the bright-pixel atmospheric correction method was activated is shown in figure 3(*d*). OC4v4 failed in the centre of the bloom where the OC4v4 estimate of chl-*a* would have exceeded $64\,\mathrm{mg\,m^{-3}}$.

As in the Bay of Biscay region, applying the IOP model to the SeaWiFS data of the Gulf of Cadiz gave unsatisfactory results. The IOP model gave a result in only 7 of the 258 potential comparisons (3%), and this was representative of its performance across most SeaWiFS images considered. Where the model gave a result, the quality of the estimate was good, estimating chl-*a* with an average low bias of 33% and a rms. difference of ca 100%. It is thought that the IOP model fails because it is sensitive to error in any of the visible bands (1–5). The vicarious validation study of Eplee *et al.* (2001) and recent work by the authors using a moored validation buoy in the English Channel (Pinkerton and Aiken 1999, Pinkerton and Lavender 2000) show that SeaWiFS is measuring L_{wn} well in bands 3–5 (490–555 nm) but under-estimating L_{wn} in bands 1 and 2 (412, 443 nm). The under-estimation at 412 nm could be as much as 50% on average. Thirty-two per cent of the $L_{wn}(412)$ values produced by SeaWiFS in the Gulf of Cadiz were negative which could explain why the IOP model works effectively on *in situ* measurements of ocean colour but poorly on remotely sensed measurements by SeaWiFS. Testing this explanation is the focus of future work.

Acknowledgments

This work was funded through the Natural Environment Research Council SeaWiFS Exploitation Initiative. The Bay of Biscay research received funding through the Programme National d'Océanographie Cotiere. Work in the Gulf of Cadiz was funded by Comision Interministerial de Ciencia y Tecnologia (CICYT) grant ESP97-1771-C02-01.

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