National Centre

for

Environmental Data and Surveillance

Temporal Variability in Chlorophyll-*a* Concentrations in the Coastal Environment

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Final Report on the National Centre for Environmental Data and Surveillance Project "Temporal variability in chlorophyll-a concentrations in the coastal environment"

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Executive Summary

The Environment Agency has a responsibility to form an opinion on the state of pollution in the environment (Environment Act 1995). This act requires the Agency to carry out its duties using a holistic and integrated approach in order to protect and enhance the environment. To this end, the Agency must respond to events in a timely and cost effective manner.

The Agency is aiding the Department of the Environment Transport and the Regions (DETR) in the determination of the eutrophic status of coastal waters. Historically, the National Coastal Baseline Survey has collected baseline water quality information, including estimates of chlorophyll-a and nutrients to assess eutrophication. This survey represents the most intensive survey of the coastal waters of England and Wales carried out to date and the results have provided an important input to an assessment of coastal water quality over the past 5 years. Review of these data, however, concluded that the temporal resolution of the survey was low, with, moreover, a long duration period for the completion of each individual survey. Sampling at not longer than monthly intervals was considered to be necessary to provide full information on temporal variability within the full coastal zone.

The National Centre for Environmental Data and Surveillance (NCEDS) considered that the collection of earth observation data, specifically SeaWiFS ocean colour imagery, in real time would allow the Agency to address one of the major variables in coastal water quality: the presence of algal blooms. Previous attempts to establish the presence and development of algal blooms using Compact Airborne Spectrographic Imager (CASI) data concluded that the collection of satellite data would be more appropriate. Satellite data allow a cost effective, daily assessment of a large part of the coastal zone extending offshore, to regions where blooms are more likely to be developing.

In April 1999 the National Centre for Environmental Data and Surveillance, initiated an investigation into the use of SeaWiFS data within the Environment Agency. Imagery was provided in near real-time under a research agreement with the North American Space Agency (NASA) for a six month period from the 1st May to 31st October 1999. The imagery was collected and processed at Plymouth Marine Laboratory (PML) and were initially received by NCEDS as true colour composite images, including a channel for water leaving radiance at 550nm (later 670 nm) and calibrated chlorophyll-a images.

This project had three key elements:

- Review of existing algorithms and recent developments
- The further quantification of chlorophyll-*a* estimates from SeaWiFS imagery for UK coastal waters
- The provision of SeaWiFS imagery in near real time to Regional representatives to allow for the early detection and monitoring of algal blooms developing offshore.

Following are three reports summarising the findings of the National Centres study to date, followed by suggestions for further work and the future of such techniques for monitoring coastal water quality.

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A Literature Review on Existing SeaWiFS Chlorophyll Algorithms and Recent Developments.

1.0 Introduction

The Sea-Wide-Field-of-view-Sensor (SeaWiFS) was launched 1 August 1997 to measure bio-optical properties of the ocean, and has provided imagery since September 1997. SeaWiFS operates in the visible light region of the electromagnetic spectrum, recording eight bands (table 1). These detect chlorophyll, suspended sediment, coloured dissolved organic matter (CDOM), and other particulate matter. Chlorophyll is the primary photosynthetic pigment found in microscopic marine plants (phytoplankton) and absorbs strongly in the red and blue, reflecting strongly in the green. The absorption of each chlorophyll pigment a, b and c (absorption in red, blue, green) in each of the SeaWiFS bands is also shown in table 1. As phytoplankton concentration increases, the reflectance decreases in the blue more than the increase in green. This enables the bands to be manipulated using algorithms to give a measurement of chlorophyll. These commonly use a ratio of bands to reduce the effect of sensor tilt angle and atmospheric effects, and may also remove sensor tilt angle and field-of-view effects.

Band	Wave-length (nm)	Colour	Measurement	Chlorophyll pigments absorption
1	412	Violet	Dissolved organic matter (violet absorption)	c, a, b
2	443	Blue	Chlorophyll (blue absorption)	c, a, b
3	490	Blue / green	Chlorophyll (blue / green absorption)	b, c
4	510	Green	Chlorophyll (green absorption)	c, b
5	555	Green / yellow	Chlorophyll (green reflection)	c, b
6	670	Red	Atmospheric aerosols	a, b
7	765	Near infra-red	Atmospheric aerosols	-
8	865	Near infra-red	Atmospheric aerosols	-

Table 1. Wavebands measured by SeaWiFS and corresponding measurement

Many algorithms were developed before the launch of SeaWiFS, using *in-situ* chlorophyll-*a* and (near-) coincident radiance measurements made from a vessel/buoy/aircraft (O'Reilly *et al.* 1998). Many chlorophyll algorithms also existed for the Coastal Zone Colour Scanner, CZCS, (Antoine *et al.*, 1996), which was in operation 1978 to 1986. The potential use of

SeaWiFS for measuring chlorophyll has therefore been evaluated using both existing and new algorithms.

2.0 Algorithm Development, Validation and Evaluation

The development and validation of algorithms has been applied to both global and region specific datasets. The former is required in operational use of SeaWiFS and towards this aim, NASA formed the SeaWiFS Bio-optical Algorithm Mini-Workshop (SeaBAM) in January 1997 (O'Reilly *et al.*, 1998). They aimed to test existing algorithms to an accuracy of ±35% over a range of 0.05 - 50 mg m^{-3} for Case I waters, *i.e.*, waters which are optically dominated by biological matter. As a result of the study, new algorithms were also developed.

SeaBAM formed one of the largest datasets of *in-situ* / radiance measurements at that time, accumulated from various sources, forming a total of 919 stations (excludes outliers). This SeaBAM dataset covers all major regions except the polar seas (table 2) and has provided a significant step in research. *In-situ* data consists of high-performance liquid chromatography (HPLC) and flourometric derived chlorophyll-*a*. Radiance values were measured in the 5 visible SeaWiFS bands from instruments on ship/buoys. These were measured mainly in-water (~90%) but all converted to give above-water remote sensing reflectances (R_{rs}). When not available, the 510 nm was substituted for with 520 nm.

Since the majority of algorithms prior to SeaWiFS were empirically based, the SeaBAM dataset was evaluated on a total of fifteen empirical and just two semianalytic algorithms.

2.1 Empirical Algorithms

Empirical algorithms are commonly used to derive chlorophyll from ocean colour measurements and are based on a statistical regression of radiance against chlorophyll. Since the transfer function between chlorophyll and radiance has not been shown as linear, empirical algorithms are normally only valid over small ranges of chlorophyll (Keiner and Brown 1998). Many are therefore designed to switch algorithms at certain thresholds.

The empirical algorithms evaluated with the SeaBAM dataset consist of a range of ratio type algorithms, each using 2 or 3 bands within the range 412 - 555 nm. The ratios were formed with either the remote sensing reflectance value (R_{rs}) or the normalised water leaving radiance (L_{WN}). Of the 15 tested, there were 6 power, 2 hyperbolic and power, 3 multiple regression and 4 cubic algorithm types. Some of these were designed to switch algorithm at a given criteria. For a full listing of algorithms, see O'Reilly *et al.* (1998).

Data Set	R_{RS}	Chl a (mean,var)	Location	Provider
BBOP	139	*0.093(0.079)	Sargasso Sea	D. Siegel
WOCE P19, A15	70	**0.133(0.012)	Equ. Pacific, Equ. Atlantic	J. Marra
EQPAC tt008, tt012	126	*0.198(0.058)	~12N-12S along 140W	C. Davis
AMT	42	**0.457(1.060)	~50N-50S, England to Falkland Islands	G. Moore
CARDER	87	**0.580(0.644)	Arabian Sea, Arabian Sea, Gulf of Mexico, N. Atlantic, Pacific Ocean	K. Carder
NABE	112	*1.686(0.813)	N. Atlantic	C. Davis, C. Trees
CALCOFI	259	**0.708(1.984)	S. Calif. Bight	G. Mitchell
MOCE 1 MOCE 2 North Sea Ches. Bay Arctic Ocean	8 5 10 10 8	***8.137(9.597)	Mont. Bay Gulf of Calif. North Sea Ches. Bay Arctic Ocean	D. Clark D. Clark R. Doerffer L. Harding G. Cota (assembled by S. Maritorena)
GLOBAL	876	***0.940(2.887)		

**denotes HPLC pigments (milligrams per meter cubed)*
***denotes fluorometric pigments (milligrams per meter cubed)*
****denotes both techniques*

Table 2. SeaBAM Data Set (O'Reilly *et al.*, 1998)

The cubic polynomial empirical algorithms were proven to be the most accurate of all empirical and semi-analytical algorithms evaluated by O'Reilly *et al.* (1998). In response, the new 'Ocean Colour' (OC) cubic polynomial algorithms were developed and tuned to the SeaBAM dataset. These all use a ratio of R_{RS} at 490 and 555 to derive chlorophyll-*a*. The variation 'OC2' attained the highest performance out of all OC and other algorithms evaluated by O'Reilly *et al.* (1998). Table 3 contains this and most other algorithms discussed in the report. With R^2 = 0.908, OC2 was chosen as the operational algorithm for SeaWiFS. Table 4 provides a summary of many of the algorithms developed and evaluated as referenced in the text, including that of OC2.

The small error remaining with OC2 is seen from its sensitivity at low R_{RS} (490) / R_{RS} (555) where chlorophyll is overestimated. In areas dominated by dissolved organic matter, suspended matter, or both, *i.e.*, Case II or coastal waters, this is by a factor of up to 16 times. The miscalculation reflects that only 20 of the 919 measurements in the SeaBAM dataset are derived from Case II waters. These waters, the North Sea and Chesapeake Bay, all recorded a high suspended sediment load, > 1mg/L. OC2 also underestimates in the intermediate range of 1-10 mg/m^3. The OC2 model has been subsequently improved upon with OC2-v2 (version 2), -v3 and -v4 (Kahru and Mitchell, 1999, O'Reilly et al 1999, McClain, 2000).

Provider	Name	Type	Algorithm
Rhea and Davis (1997)	Carder model	semianalytic	see Carder *et al.* (submitted)
O'Reilly *et al.* (1998)	Carder model	semianalytic	see Carder *et al.* (1999)
O'Reilly *et al.* (1998)	Garver/Siegel model	semianalytic	see Garver and Siegel (1997)
O'Reilly *et al.* (1998)	OC2	empirical, modified cubic polynomial	chl = 10 ^(a0 + a1*R + a2*R^2 + a3*R^3) + a4 R = (log (R_{rs}(490)/ R_{rs}(555)) a = [0.341, -3.001, 2.811, -2.041, 0.004]
Habbane *et al.* (1998)	-	empirical spectral curvature model	log(C) = 0.92 - 0.46Δ^2logR_{oass}(555)
Kahru and Mitchell (1999)	CAL-P6	empirical, sixth-order polynomial	chl = 10 ^(a0 + a1*R + a2*R^2 + a3*R^3 + a4*R^4 + a5*R^5 + a6*R^6) R = (log (L_{NW}(490)/ L_{NM}(555)) a = [0.565, -2.561, -1.051, -0.294, 5.561, 3.130, -10.816]
Maritorena, (1998)*	OC2-v2	empirical, modified cubic polynomial	chl = 10 ^(a0 + a1*R + a2*R^2 + a3*R^3) + a4 R = (log (R_{rs}(490)/ R_{rs}(555)) a = [0.2974, -2.2429, 0.8358, -0.0077, 0.0929]
Wernard *et al.* (1998)	-	empirical	chl = 3.4 * (R510 / R555)$^{-3.65}$
		MRA	chl = -96.5 + (20.3*R443/510) + (34.1*R490/10) + (50.2*R555/R510)
Keiner and Brown (1999)	-	neural networks	-
O'Reilly *et al.* (1999)	OC2v3	empirical, modified cubic polynomial	-

** pers. communication between Maritorena, Kahru and Mitchell (1998)*
For full equation and explanation see individual references

Table 3. Formulations of chlorophyll algorithms

In a study made by Kahru and Mitchell (1999), OC2 and OC2-v2 were tested against a subset of the SeaBAM dataset, the California Cooperative Oceanic Fisheries Investigation (CalCOFI) data. Collected from the California Current, CalCOFI had previously formed $^1/_3$ of the SeaBAM dataset and was expanded with new data for this study (n = 348). Kahru and

Mitchell (1999) prove that OC2-v2 does improve the accuracy at high values of chlorophyll, though both OC2 and OC2-v2 under-perform in the low and intermediate (table 4).

In comparison to the SeaBAM dataset, CalCOFI data are collected and processed similarly, with a greater representation of eutrophic waters. Kahru and Mitchell (1999) note that one major drawback of the SeaBAM dataset is that it contains a large source of variation. This includes: measuring instruments and processing; adjustment to SeaWiFS bands; radiometric calibrations and surface extrapolation; and there is no correction for instrument self-shading (Kahru an Mitchell, 1999). There is also natural variability in bio-optical provinces, which do not give a complete coverage of the world's average trophic state. Antoine *et al.* (1996) have found the global ocean mean to be 0.19 μg l^{-1} whereas the SeaBAM data set has a mean of 0.27 μg l^{-1}, ranging 0.019 to 32.79 μg l^{-1}. This reveals the overrepresentation by mesotrophic and eutrophic waters (0.1 - 1.0 and >1.0 μg l^{-1} respectively). In contrast, the CalCOFI data is region-specific but still encompasses a large range of chlorophyll measurements, 0.05 - 32.5 μg l^{-1}, where > 15μg l^{-1} normally represents red tides. It does not, however, contain measurements from nearshore waters high in suspended sediment.

A third algorithm, CAL-P6, was developed with the CalCOFI data (Kahru and Mitchell, 1999). It is similar to OC2 and OC2-v2 expect it swaps R_{rs} for L_{WN} in the ratio of the 490 and 555 nm bands. It also uses a 6th order polynomial instead of the 3rd in OC2/-v2.

Cal-P6 gives the best correlation overall in the CalCOFI dataset with R^2 = 0.96. Though tuned to the CalCOFI data, it has been adjusted to accommodate for waters outside the range of the CalCOFI dataset and does therefore not achieve 100% correlation. At low chlorophyll-*a*, the L_{WN} (490) / L_{WN} (490) was forced to approach clear water whereas at high values, the curve given by chl-*a* against the L_{WN} ratio was forced towards the higher chlorophyll-*a* values. These restrictions lead the CAL-P6 algorithm to apply to a range of chlorophyll-*a* between 0.02 and 50 mg m^{-3}, and a L_{WN} ratio of more than 0.26. In comparison, tested on the SeaBAM dataset, the three algorithms produce similar R^2 values (0.91-92).

Validation was also carried out by Kahru and Mitchell (1999) using 27 pairs of *in-situ* / SeaWiFS measurements. These were taken up to ±4 hours apart, using 3x3 pixel average values from the SeaWiFS images. All algorithms overestimated at high *in-situ* values, and underestimated at low values. This was traced to overestimation of the L_{WN} (490) and (555) by SeaWiFS. They suggest that the inaccuracies are highly dependent on atmospheric correction errors. The correlations did, however, return R^2 values of 0.90 - 0.93, with CAL-P6 performing best.

The third OC algorithm, OC3, was developed using the updated SeaBAM dataset (CalCOFI additions) combined with the Harding data (O'Reilly *et al.* 1999). With a total of 1362 data pairs, this includes high chlorophyll measurements in Chesapeake Bay and nearby waters (Harding data). Whilst it has no significance to changes at low to mid chlorophyll, it exceeds version 2 above *in-situ* measurements of 10 μgl^{-1}. A fourth OC2 algorithm is currently being developed (McClain, 2000) and is aimed to improve accuracy in high latitude and coastal waters. This is being addressed by the SeaWiFS reprocessing stage 3, with an expanded and refined dataset.

Use of spectral curvature models have recently shown to improve the accuracy of empirical algorithms by reducing the solar angle effect. Habbane *et al.* (1998) have tested their algorithm using 20 points of *in-situ* chlorophyll and above water radiance values in the Gulf of St Lawrence. The regional algorithm was accurate to within 23%, well within the 35% required accuracy for SeaWiFS. The region is, however, characteristically low in SPM, *i.e.*, does not give a good global representation.

2.2 Semi-analytical Algorithms

Semi-analytical, or semi-empirical algorithms differ from empirical in that they allow the parameterisation of several terms, for example gelbstoff, or dissolved organic matter. Created with cubic or power polynomials, they are In fact analytical algorithms that can be inverted to give back any term. This additional data are valuable for Case II waters.

The two semi-analytical models evaluated on the SeaBAM dataset (O'Reilly *et al.*, 1998) are based on the $b_b / (a + b_b)$ to R_{RS} relationship, where 'b_b' and 'a' are the backscattering and attenuation coefficients, and R_{RS} the remote sensing reflectance. The Carder model (Carder *et al.* 1999) uses R_{RS} at 675 to measure the absorption coefficient of phytoplankton, $a_{ph}(675)$, and absorption coefficient of coloured dissolved organic matter (CDOM) at 400, $a_g(400)$. From these, the chlorophyll concentration is measured empirically. When $a_{ph}(675)$ is outside a given range, an alternative ratio of ($R_{RS}490/ R_{RS}555$) is used. The Carder model was designed for subtropical, unpackaged pigment data and a second Carder model was adapted for packaged pigments, with global application.

The second semi-analytical model tested is the Garver/Siegel model (Garver and Siegel, 1997), adapted for use with the SeaBAM dataset. This derives the chlorophyll-*a* concentration, the absorption coefficient due to phytoplankton, the absorption coefficient due to other particulate and dissolved matter and the backscattering coefficient of particles, all at the same wavelength of 441 nm.

Though the semi-analytical algorithms were overall, out performed by the empirical models, the Carder model did rival the accuracy of several of the best empirical algorithms. One factor contributing to the Carder model's success is its requirement to tune to the provided *in-situ* data.

One of constraints of the semi-analytical models, however, is that the parameterisation is considered more suitable to individual regions, *i.e.*, those with similar bio-optic characteristics. In addition, they can be based on false assumptions, for example, the slope in detrital absorption is constant in the ocean, or that the specific coefficient of phytoplankton is wavelength dependent. It is also considered that using 4+ wavebands, as in the Carder model, requires a more consistent dataset. This is in contrast to the 2 or 3 wavebands used in empirical algorithms, which enable them to maintain their accuracy in a wider geographical area.

The same subtropical Carder model, evaluated by Rhea and Davis (1997), has previously shown greater performance, despite being used in the equatorial Pacific, outside the 'design' region. They also used a much reduced dataset of 32 stations but these did consist equally of Case I and Case II waters, unlike the SeaBAM dataset (predominantly Case I). Through manipulation of the algorithm, they achieved a correlation with $R^2 = 0.908$ (table 4). This correlation was possible through removing 4 outliers and subtracting 0.05 $\mu g\ l^{-1}$ from each modelled chlorophyll value.

In addition to those tested by O'Reilly *et al.*, semi-empirical algorithms have been used with multiple regression analysis (MRA) by Wernard *et al.* (1998), with data from the English Channel and south-east corner of the North Sea. This consisted of airborne CASI (Compact Airborne Spectrographic Imager), CORSAIR (Coastal Optical Remote Sensing Airborne Radiometer) and spectrometry derived radiance values. Through the use of principal component analysis, the spectral signature can be given by the linear combination of only 3-4 bands in the visible. In this study however, the MRA was outperformed by a standard ratio empirical algorithm (table 3), though both were of poor accuracy.

2.3 Neural Networks

A recent addition in the use of algorithms, to derive chlorophyll measurements from radiance values, is to use neural networks (Krasnopolsky, 1995). These are effectively trained to 'learn' the spectral signature, adjusting weights during the process to achieve maximum accuracy. Neural networks model a large range of transfer functions and are able to return a variety of non-linear behaviour. This is ideal in ocean bio-optics where several parameters influence ocean colour, especially in Case II waters.

A study made by Keiner and Brown (1999) examines the SeaBAM dataset using neural networks (NN). To create a comparison with the SeaBAM study (O'Reilly *et al.*, 1998), they use the 443 and 555 wavebands as well as 490 and 555 in two separate networks, and 5 SeaWiFS visible bands in a third. They are run by inserting a random set of weights which are adjusted at each 'hidden node' as data are introduced. After 10 nodes, the accuracy was found to plateau. An increasing number of nodes would continue to improve the algorithm at first but also slows computation time and eventually tunes to the noise signal.

The NN outperforms OC2 when using both the two different wavebands and with all 5 bands. The 2 band NNs do, however, overestimate in the low chlorophyll range and the 490-555 NN underestimated at high chlorophyll levels. The additional 3 bands increased the correlation coefficient in the training set from 0.94 to 0.96 and decreased the root mean square error from 0.14 and 0.15 to 0.11. The rms error increases in the validation (10% of the SeaBAM data were kept for validation of the NN) to 0.13 but is still significantly superior to the OC2 algorithm (rms error 0.17, R^2 0.92). These results show that the information given by the extra 3 bands is a significant input to derive chlorophyll.

2.4 Case II Waters

Coastal waters and other regions high in suspended sediment are generally seen to reduce the performance of algorithms. This is due to the decreased covariance between phytoplankton and gelbstoff concentrations in these highly dynamic waters. Turbid waters may also distort measurements, where non-zero radiance values in the infrared are not accounted for in atmospheric models.

Bernard *et al.* (1998) have studied the effects of gelbstoff in South African waters which are known to be highly variable and productive. There, they found that the periods around bloom scenes are the most sensitive. As phytoplankton populations collapse, they produce large amounts of organic compounds including humic acid. This is known to exaggerate the short term variations in phytoplankton, introducing errors in the modelled chlorophyll. The algorithm used is the Carder model as default and a CZCS-style algorithm for when certain criteria fail (chl-*a* absorption at 675 nm and gelbstoff at 400 nm return no value). It was found that the algorithm faltered most at high chl-*a* concentrations, > 3 $\mu g\ l^{-1}$, where the CZCS algorithm was used. The Carder model achieved greater accuracy when used at < 3 $\mu g\ l^{-1}$ and improved with increasing levels of gelbstoff.

The standard band ratio type of algorithm, as used by Bernard *et al.* (1998) and many of those previously discussed, fails to give absorption and scattering information. This can indicate the presence of SPM and CDOM and this is one focus for new algorithms, with the multiband approach.

Robinson (2000) has used the multiband approach for detecting (not measuring) coccolithophores, a type of phytoplankton. They have updated the criteria developed by Brown (1995) for use with SeaWiFS in the Bering Sea, which is given by:

L_{WN} (555) $\geq$ 0.81 (clear water) and
L_{WN} (443) $\geq$ 1.1 (clear water and possibly sediments) and
L_a (670) $\leq$ 1.1 (haze) and
0.60 $\leq$ L_{WN} (443) / L_{WN} (555) $\leq$ 1.10 (sediments, red tide and haze) and
0.90 $\leq$ L_{WN} (510) / L_{WN} (555) $\leq$ 1.32 (unknown conditions) and
0.60 $\leq$ L_{WN} (443) / L_{WN} (510) $\leq$ 0.92 (sediments and haze),

The conditions given after each are masked out by the given criteria.

Focusing on the longer wavebands for sediment distinction, studies in the China seas (He *et al.*, 2000) have used an additional 682 nm channel, as measured in the field (not available on SeaWiFS). The hyperspectral semianlaytical model used returned modelled chlorophyll with only a small error of 18%.

3.0 Future Improvements on Chlorophyll Algorithms

Studies have shown that the 2 band ratio type algorithm may be limited in coastal waters but has a relatively good global application. Improvements are presently underway on the OC algorithm in the SeaWiFS reprocessing stage. In addition, NASA is examining effects from: whitecapping, sensor degradation, ozone, sun glint, the atmosphere, aerosols and out of band corrections. Also, improved IR reflectance corrections (bands 7 and 8) are expected to reduce negative L_{WN} values and reduce the overestimation in coastal waters. Plymouth Marine Laboratory (PML) are due also to update their atmospheric correction software to SeaDAS-4.

Semi-analytical models and neural networks use a multiband approach and this is advantageous to Case II waters, in a more region-specific capability. These are better suited to explain the complex pattern of relationships given by absorption for chlorophyll, SPM, CDOM and other particulate matter. Use of additional bands also offers a similar potential for coastal water empirical algorithms, for example with the non-visible bands and red channel.

In summary, there is potential for all types of algorithm discussed. There is a great need, however, for more evaluation on actual SeaWiFS data as opposed to radiance data collected from ships or buoys. The Environment Agency data will provide a significant dataset towards this aim.

Provider	Region	*In-situ* Measurements	Radiance Measurements
(1) Rhea and Davis (1997)	equatorial Pacific (model used developed for subtropical)	HPLC n = 32 (16 Case I, 16 Case II)	spectrometer in water
(2) Rhea and Davis (1997)	equatorial Pacific (model used developed for subtropical)	HPLC n = 23	spectrometer above water (discarding 4 outliers and with -0.05 mean offset)
O'Reilly *et al.* (1998)	global coverage, except high latitude and Arctic	SeaBAM dataset flourometric and HPLC n=919	near-surface radiometers from ship/buoy
Habbane *et al.* (1998)	Gulf of St Lawrence (low in SPM)	Spectrophotometry n = 20	hand-held spectroradiometer
Wernard *et al.* (1998)	English Channel and SE of North Sea	HPLC and flourometer	airborne CASI/CORSAIR and spectrometer
(1) Kahru and Mitchell (1999)	California Current low in SPM, frequent red tides	CalCOFI dataset ($^1/_3$ of SeaBAM) flourometric and SeaBAM n = 348	underwater radiometers
(2) Kahru and Mitchell (1999)	California Current low in SPM, frequent red tides	CalCOFI dataset n = 27	SeaWiFS

Table 4. Summary of algorithm evaluation and performance

Algorithm	Statistics/Results
Carder model	$R^2 = 0.543$, slope = 0.618
Carder model	$R^2 = 0.908$, slope = 0.937
15 empirical and 2 semi-analytical (including Carder model, 1998) tested and OC2 developed	OC2: $R^2 = 0.918$, rms = 0.172 C_a^*: $R^2 = 0.872$, rms = 0.284 C_g^*: $R^2 = 0.876$, rms = 0.213
spectral curvature empirical model	$R^2 = 0.95$ accurate to within 23%
ratio	rms = 2.2
MRA	rms = 2.7
OC2	$R^2 = 0.91/0.92$, rms = 0.21/0.17**
OC2-v2	$R^2 = 0.95/0.91$, rms = 0.24/0.19
CAL-P6	$R^2 = 0.96/0.92$, rms = 0.12/0.23
OC2	$R^2 = 0.90$, rms = 0.31
OC2-v2	$R^2 = 0.92$, rms = 0.27
CAL-P6	$R^2 = 0.93$, rms = 0.26

Provider	Region	*In-situ* Measurements	Radiance Measurements
Keiner and Brown (1999)	global coverage, except high latitude and Arctic	SeaBAM dataset n = 919	near-surface radiometers
O'Reilly *et al.* (1999)	SeaBAM-2 and Harding data (Chesapeake Bay)	n = 1362 total (n = 197 Harding)	various
He *et al.* (2000)	China seas, near mouth of R. Yangtze		Simulated SeaWiFS channels and 682nm

Note - all n = etc values exclude outliers not used in correlation

* *C_s = Carder model, subtropical, C_g = Carder model, global*

** *First value is using CalCOFI* dataset, *second is with SeaBAM*

Table 4. Summary of algorithm evaluation and performance (cont.)

Algorithm		Statistics/Results
neural	- training (5 bands)	$R^2 = 0.964$, rms = 0.113
networks	- validation " "	$R^2 = 0.959$, rms = 0.126
	- training (443/555)	$R^2 = 0.944$, rms = 0.141
	- training (490/555)	$R^2 = 0.935$, rms = 0.151
OC2v3		outperforms OC2 for > 10 $\mu g l^{-1}$ similar for 0.01 - 10 $\mu g l^{-1}$
hyperspectral semi-analytical algorithm		<18% error

4.0 References

Antoine, D., André, J.M. and Morel, A. 1996. Oceanic primary production, 2, Estimation at global scale from satellite (CZCS) chlorophyll. In *Global Biochem. Cycles*, Vol. 10(1), pp 57-69.

Bernard, S., Probyn, T.A. and Shillington, F.A. 1998. Towards the validation of SeaWiFS in Southern African waters: the effects of Gelbstoff. In *South African Journal of Marine Science*, Vol. 19, pp 15-25.

Brown, C.W. 1995. Classification of coccolithophore blooms in ocean colour imagery. In Case Studies for SeaWiFS Calibration and Validation, Part4, NASA Technical Memo, 104566, Hooker, S.B., Firestone, E.R., Acker, J.G., Eds., NASA Goddard Space Flight Center, Greenbelt, Maryland, Vol. 28, pp 13-19.

Carder, K.L., Hawes, S.K. and Lee. Z. (submitted) SeaWiFS algorithm for chlorophyll and coloured dissolved organic matter in a subtropical environment. In *Journal of Geophysical Research.*

Carder, K.L., Chen, F.R., Lee, Z.P., Hawes, S.K. and Kamykowski, D. 1999. Semi-analytic Moderate Resolution Imaging Spectrometer algorithms for chlorophyll a and absorption with bio-optical domains based on nitrate-depletion temperatures. In *Journal of Geophysical Research-Oceans*, Vol. 104(C3), No. 5, pp 5403-5,421.

Garver, S.A. and Siegel, D.A. 1997. Inherent optical property inversion of ocean colour spectra and its biogeochemical interpretation .1. Time series from the Sargasso Sea. In *Journal of Geophysical research - Oceans.* Vol. 102(C8), No. 18, pp 607-18,625.

Habbane, M., Dubois, M.I., El-Sabh, M.I and Larouche, P. 1998. Empirical algorithm using SeaWiFS hyperspectral bands: a simple test. *Technical note,* In *International Journal of Remote Sensing*, Vol. 19(11), pp 2161-2169.

He, M.X., Liu, K.P, Li, L.P, Chen, K.L and Lee, Z.P. 2000. Retrieval of chlorophyll from remote sensing reflectance in the China seas. *Applied Optics*, Vol. 39(15), No. 2,pp 467-2,474.

Kahru, M. and Mitchell, B.G. 1999. Empirical chlorophyll algorithm and preliminary SeaWiFS validation for the California Current. In *International Journal of Remote Sensing*, Vol. 20(17), No. 3,pp 423-3,429.

Keiner, L.E. and Brown, C.W. 1998. Estimating chlorophyll concentrations with neural networks. In *International Journal of Remote Sensing*, Vol. 20(1), pp 189-194.

Krasnopolsky, V., Breaker, L. and Gemmill, W. 1995 A neural network as a nonlinear transfer model for retrieving surface wind speeds from the special sensor microwave imager. In *International Journal of Remote Sensing*, Vol. 20(1), pp 195-200.

O'Reilly, J.E., Maritorena, S., Mitchell, G., Siegel, D.A., Carder, K.L., Garver, S.A., Kahru, M. and McClain, C. 1998. Ocean colour chlorophyll algorithms for SeaWiFS. In *Journal of Geophysical Research*, Vol. 103(C11), No. 24, pp 937-24,953.

O'Reilly, J.O, Maritorena, S., Harding, L., Magnuson, A. and Zibordi, G. 1999. *Website* http://*seawifs.gsfc.nasa.gov/SEAWIFS/RECAL/*

McClain, C. 2000. *SeaWiFS data users, email*

Rhea, W.J. and Davis, C.O. 1997. A comparison of the SeaWiFS chlorophyll and CZCS pigment algorithms using optical data from the 1992 JGOFS Equatorial Pacific Time Series. In *Deep Sea Research*, Vol. 44(9-10), pp 1907-1925.

Robinson, W.D. 2000. The updated SeaWiFS coccolithophore algorithm. *Draft for SeaWiFS Postlaunch Technical Report Series Volume 9.*

Wernard, M.R., Shimwell, S.J., Boxall, S. and van Aken, H.M. 1998. Evaluation of specific semi-empirical coastal colour algorithms using historic data sets. In *Aquatic Ecology*, Vol. 32, pp 73-91.

Testing of SeaWiFS Chlorophyll Algorithms using an Environment Agency and Plymouth Marine Laboratories Dataset.

1.0 Introduction

The purpose of this project is to test the accuracy of three SeaWiFS chlorophyll algorithms, using radiance values derived from SeaWiFS, against *in-situ* measurements from coastal England and Wales. The SeaWiFS working NASA algorithm is tested and also two currently under validation: the modified NASA algorithm, being developed at the National Centre for Environmental Data and Surveillance (NCEDS) and another from Plymouth Marine Laboratories (PML). All Environment Agency Regions with coastal borders have contributed data to the project, as well as data from PML, comprising over 6000 *in-situ* measurements.

2.0 Method

2.1 *In-situ* Data

The Regions were contacted in December 1999 for *in-situ* chlorophyll measurements between April and September 1999. Due to the resolution of SeaWiFS imagery, the data were needed at a distance greater than 1km offshore to remove any land signal. In some Regions, this restriction has significantly reduced their contribution. Table 1 shows the number of measurements received for the period 14 April to September 21, during which SeaWiFS imagery is available. Approximately one third of the data were discarded where imagery was not available. Data were also retrieved from the Northeast Region but, as these lie out of the SeaWiFS imagery extent, have not been included.

EA Region/Other	Contact Name	No. of measurements supplied
Anglian	Mike Best	3610
Southern	Dave Lowthian	119
Wales	Bob Phillips	59
Northwest	Peter Jones	46
Southwest	Bob Davidson	5
PML	Sam Lavender	4
TOTAL		3843

Table 1. *In-situ* measurements collected with same-day SeaWiFS imagery available.

The chlorophyll data have been collected by methods including *in-vivo* Photometric (IVP), spectrophotometry and high-performance liquid chromatography (HPLC). These originate from a collection of standard surveys, *e.g.* baseline surveys, and Anglian's routine monitoring;

and specific surveys, *e.g.* PML's bloom survey and southern region's Dangerous Substances Directive (DSD) site and new outfall measurements.

2.2 Algorithms

The working SeaWiFS algorithm was selected by NASA from SeaBAM (the SeaWiFS Bio-optical Algorithm Mini-Workshop). In this study, a number of algorithms were evaluated against a global dataset of near-coincident radiance values, corresponding to the SeaWiFS wave bands, and *in-situ* measurements (O'Reilly *et al.* 1998). As a result of the study, the Ocean Chlorophyll 2 'OC2', modified cubic polynomial algorithm was developed, as tuned to the SeaBAM dataset, later updated to the OC2v2 (Kahru and Mitchell, 1999). OC2v2, now used by SeaWiFS to measure chlorophyll concentration, uses the ratio of the remote sensing radiance at 490 and 555 nm, where the band ratio, X is given by:

$$X = \log 10 \left(R_{RS}490/R_{RS}555 \right)$$

And chlorophyll, C:

$$C = 10^{(0.2974 - 2.2429X + 0.8358X^2 - 0.0077X^3)} - 0.0929$$

The NASA algorithm is based on Case I waters defined as, waters low in suspended sediments and other particulate matter (biologically dominated). Almost all the *in-situ* data collected by the Environment Agency are in coastal waters, which are mainly Case II (high sediment and coloured dissolved organic matter). As a result, the chlorophyll measurements are normally overestimated. To resolve the unsuitability of this algorithm in UK waters, NCEDS have used an imaging differencing technique to mask out regions of high suspended particulate matter (SPM). This modified NASA algorithm limits OC2v2 to apply only when the normalised water leaving radiances at 555 and 670 nm are less than 0.5 μEcm^{-2}. Since this masked out the majority of the Agency/PML data assessed here (leaving eight datasets), the algorithm was altered to use only the 670 nm channel, maintaining the 0.5 μEcm^{-2} threshold.

The third algorithm, still under validation at PML (Groom, 2000), is also designed to reduce the effects of scattering and absorption from SPM. This uses the normalised water-leaving radiance at six visible wavebands, 412, 443, 510, 555 and 670 nm in a radiative transfer model based on known absorption and scattering relationships, using an inverse modelling technique.

2.3 Earth Observation Data - SeaWiFS

SeaWiFS (Sea-viewing Wide Field-of-view Sensor) imagery was supplied to the Environment Agency under a research agreement with NASA for the period April to September 1999. SeaWiFS imagery is received by the NERC Dundee Satellite Receiving Station and transferred to the Plymouth Marine Laboratories (PML). There, the Remote Sensing Group processes the imagery, correcting for atmospheric affects, using the SeaWiFS Data Processing System (SeaAPS). This part of the project, however, has used them primarily as a source of data subsequent to retrieval of *in-situ* measurements.

Imagery is available to the Environment Agency from up to 4 satellite passes a day in the UK. This covers all waters offshore of England and Wales apart from some areas in the far north. The passes vary between 11am and 3pm each day. For every satellite pass, 5 products were supplied in the form of imagery:

ac	chlorophyll (NASA Algorithm)	
bc	new PML chlorophyll algorithm (still under development)	
ar	nLw 555 *i.e.* the SeaWiFS green waveband	normalised water-leaving radiances
br	nLw 670 *i.e.* the SeaWiFS red waveband	as used in modified NASA algorithm
(ao	colour composites)	

Figure 1 shows one of the clearest images available over the period, 29 July 1999. The pixel shading from pink to blue/purple represents increasing concentration in chlorophyll-*a*, as derived from the OC2v2 algorithm. The higher values are notably associated with coastal waters, in particular along the coastline of Wales and the Severn and Thames estuaries. Also visible in the image are locations of the 3843 *in-situ* measurements held by the Agency.

Cloud-free imagery and *in-situ* data pairs were matched by a program run at PML, extracting the values from the first four products. This derived the average of a 3x3 square area from the imagery, centred on the pixel containing the *in-situ* measurement. The program output allowed data to be discarded in areas of cloud, leaving approximately half of the measurements (1802) paired to at least one of the 3 algorithms. This is equal to almost one third of the original *in-situ* dataset.

This remaining dataset was examined visually, using ERDAS Imagine and Arc View, to determine any remaining atmospheric affects on the 3x3 average values. Towards this aim, the single pixel values of chloropyll-*a* were also extracted from the imagery, using ArcView scripts. Due to time constraints, this was carried out on the NASA chlorophyll algorithm only ('ac' product). The dataset was then cut down again where these values returned zero values (cloud). The single pixel values were also valuable to compare against the 3x3 averages to determine the level of variability in the near vicinity.

Each point was examined on the corresponding SeaWiFS chlorophyll image to examine the effect of land and/or cloud/aerosols on the average and single values, performed through personal judgement. Additional observations were made in proximity to major estuaries, where sediment is likely to affect the algorithms. In order to give such analysis in the time available, it was necessary to cut down the Anglian dataset. These were reduced by a taking an even proportion by date and *in-situ* chlorophyll concentration, leaving 10% of the Anglian data, and approximately 200 for analysis in total.

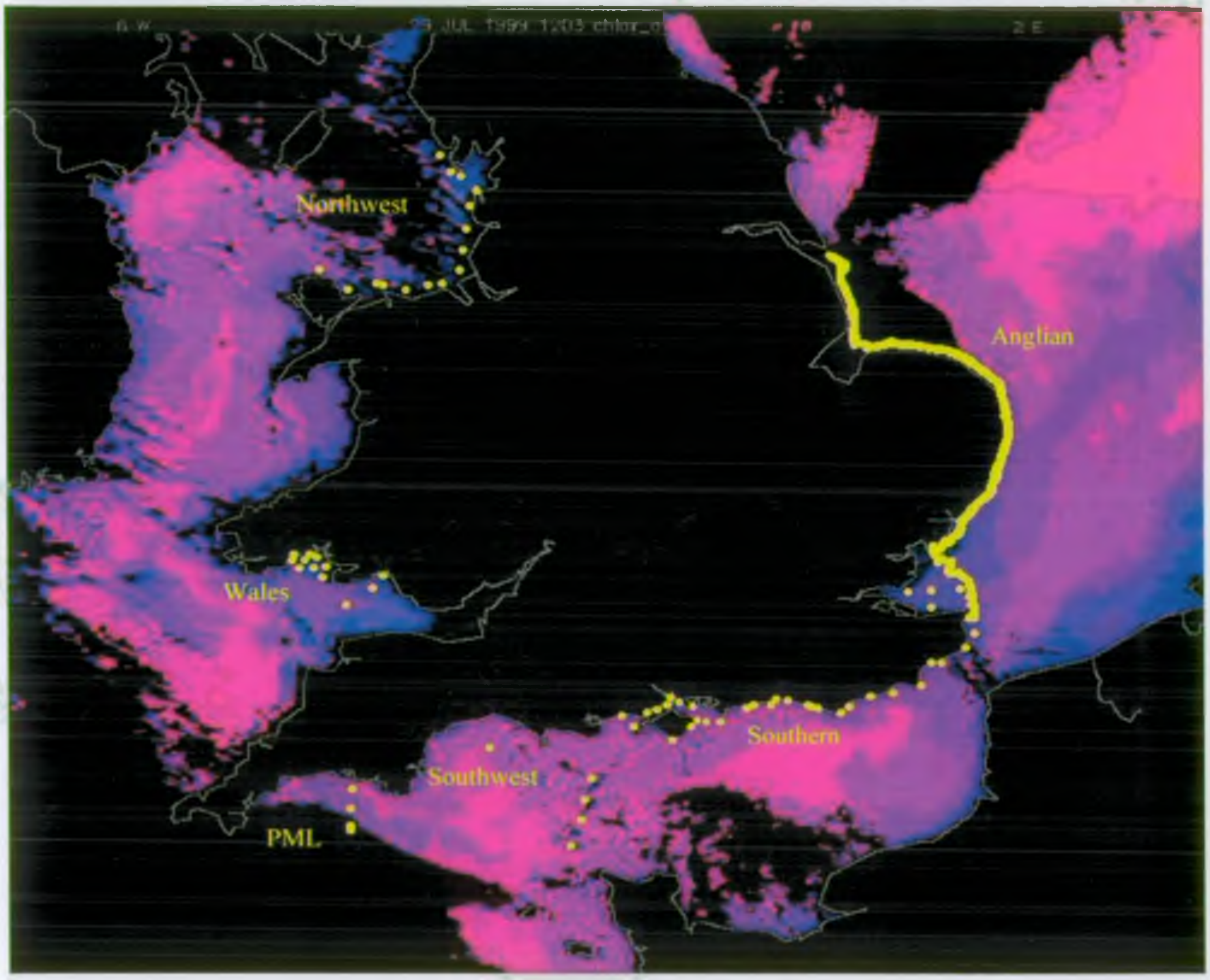

Figure 1. Example SeaWiFS Image, 29 July 1999 12:03 showing location and source of all in-situ measurements available for the April - September 1999 period.

3.0 Results

The results presented here are based on all SeaWiFS data that are considered to have no possibility of atmospheric influence. Plots where there may be or is clear evidence of atmospheric effects, reveal a large scatter in the correlation and it is on this basis they have been excluded from the analysis. (These datasets do, however, include the majority of *in-situ* chlorophyll-*a* measurements >5 $\mu g l^{-1}$). Between the three algorithms, this provides a total of 28 separate datasets for analysis. These include data from Anglian and Southern Regions, Environment Agency Wales and PML. Imagery for the Northwest data was either cloudy or pixels were affected by cloud in the vicinity of the *in-situ* data points.

The final dataset selected is dominated by *in-situ* data in the range of 0 - 5 $\mu g l^{-1}$ (figure 2). The greatest correlation is from the 3x3 modified NASA algorithm, which is designed to mask out waters high in SPM. This is clear in figure 2 where the high erroneous 3x3 NASA values, centred between approximately 0.5 and 2.0 $\mu g l^{-1}$, are masked out. With a correlation coefficient of 84% (table 2), and slope of 1.4, this modification clearly improves on 59% (slope 1.3) given by the 3x3 NASA algorithm and 35% of the 1x1 NASA algorithm. With the limited data, the PML algorithm does not show any correlation, with R^2 = 1%. Although the first three algorithms perform moderately well, all three overestimate chlorophyll-*a* concentration at most ranges.

Algorithm	R^2	Intercept	Slope
1x1 NASA	0.3482	3.7339	0.6998
3x3 NASA	0.5923	2.3033	1.2782
3x3 MOD NASA	0.8413	1.4704	1.4036
3x3 PML	0.0138	3.7773	-0.2736
SeaBAM	0.6364	3.0341	0.7636

Table 2. Regression analysis

Both the 3x3 NASA and 3x3 MOD NASA algorithms overestimate the chlorophyll, with slopes >1. This exaggeration is reinforced when examining the data against the SeaBAM dataset as in figure 3 (correlation statistics also in table2). With the exception of one point derived from the PML algorithm, all other Agency points appear approximately in trend with, but transposed slightly above, the SeaBAM dataset. This is most likely to be caused by high turbidity and increased SPM. To evaluate this hypothesis, the Anglian data was analysed further, as it includes measurements of *in-situ* turbidity, taken alongside chlorophyll-*a*. Figure 3 also highlights the three Anglian points EA1353, EA1400 and EA2221, whose measured and modelled characteristics are given in table 3. (The turbidity measurements of May and June are uncalibrated so act only as a guide; ±50% errors are expected from the data.)

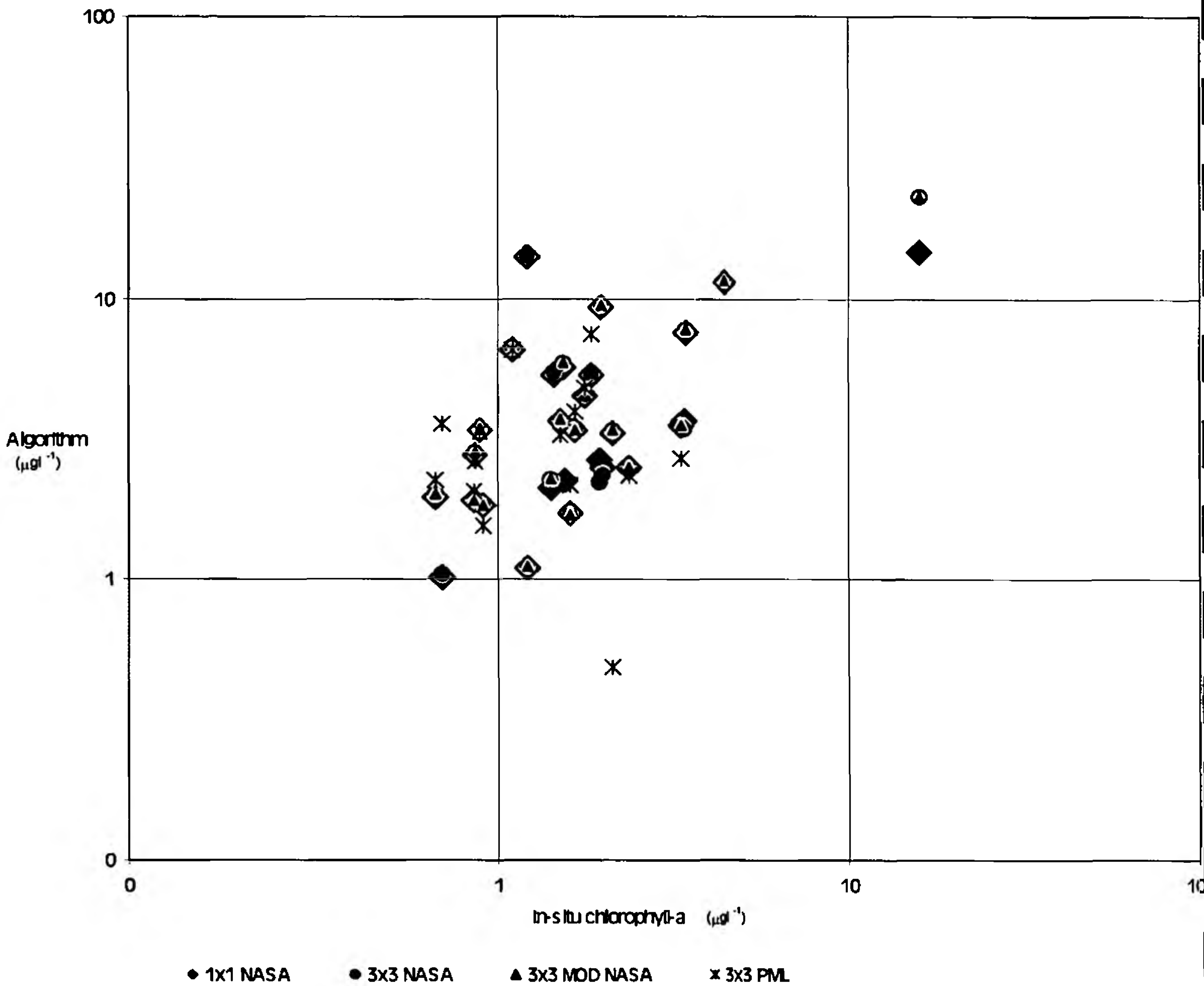

Figure 2. Comparison of algorithm performances

EA2221 records high turbidity in both the ship measurements, >40 Formazin turbidity units, and from the normalised water leaving radiance at 555 and 670 nm, >3 μEcm^{-2}. In contrast, EA1353 and EA1400 measure low turbidities of <3 Formazin turbidity units and radiances

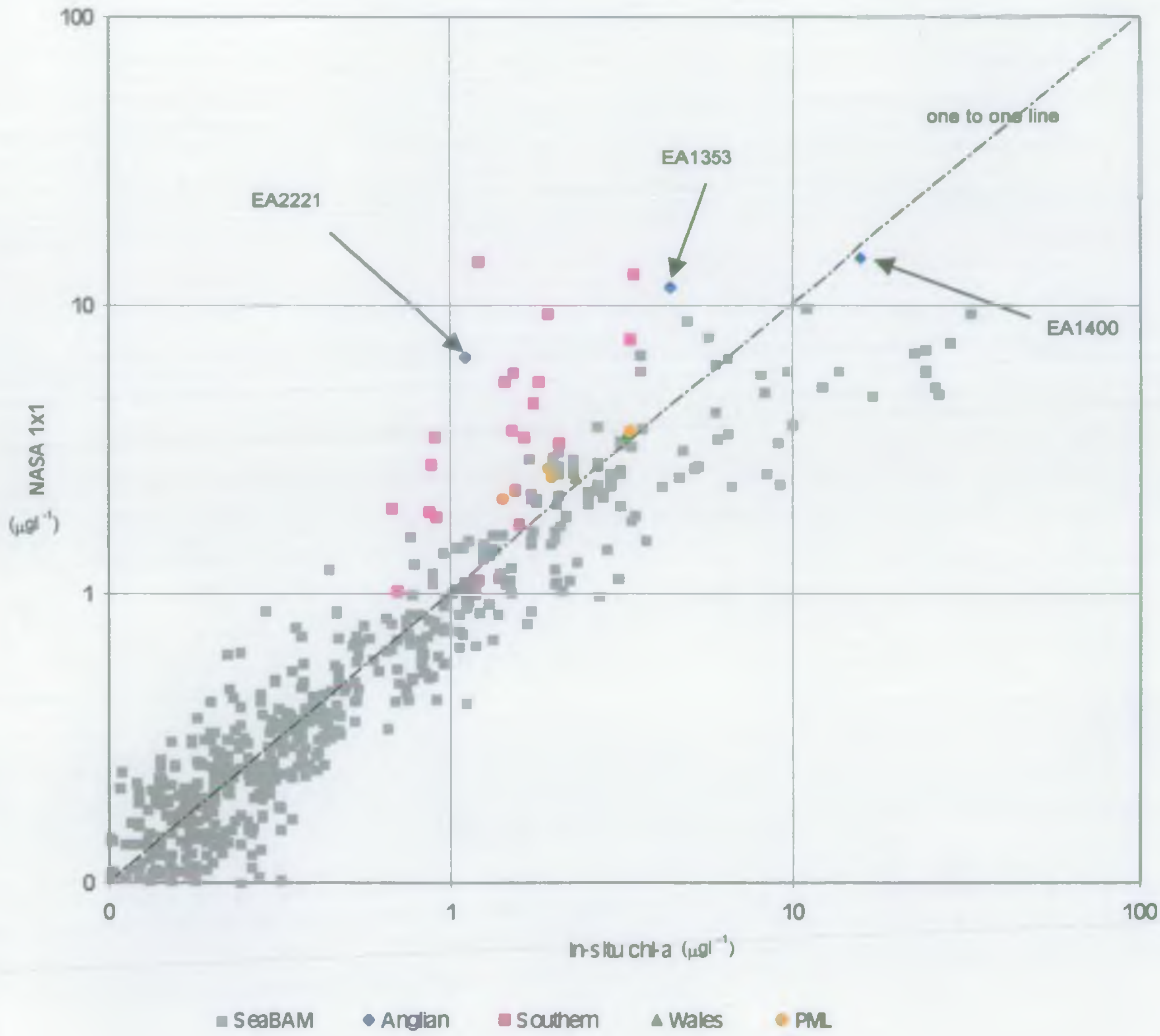

Figure 3. Modelled and in-situ data in comparison to the SeaBAM dataset, with examination of Anglian data points. (Also see table 3)

EA ID	EA1353	EA1400	EA2221
Date	27/05/9	29/06/9	23/07/9
In-situ time	20:04	10:34	10:50
Satellite pass time	13:09	12:54	12:33
In-situ chl-a (μgl^{-1})	4.40	15.90	1.10
In-situ turbidity (Formazin turbidity unit)	2.97	1.80	41.40
1x1 NASA chl-a (μgl^{-1})	11.48	14.62	6.61
3x3 NASA chl-a (μgl^{-1})	11.64	23.00	6.75
3x3 PML chl-a (μgl^{-1})	0.00	0.00	6.62
3x3 nLW555 μEcm^{-2}	1.71	0.74	5.69
3x3 nLW670 μEcm^{-2}	0.19	0.12	3.94

Table 3. East Anglian data with turbidity

<0.5 μEcm^{-2} at 670nm and <2 μEcm^{-2} at 555nm. The first is, not surprisingly, exaggerated 6-fold by all three algorithms, while the EA1353 is nearly 3 times over and EA1400 within the ±35% error requirement (given by NASA) for the 1x1 NASA algorithm. This illustrates well the algorithm performance relative to water properties, and indicates the sources of error in table 2.

The data are further separated into regional and seasonal comparisons in figures 4 and 5 respectively. The PML data does not appear in the 3x3 PML algorithm charts as this product was not available. All algorithms show that the Wales and, where shown, PML data are measured most accurately by SeaWiFS, though with only a few datasets, is not conclusive. The Southern data forms the widest range with consistent overestimation at all ranges. The Anglian data represents the maximum in-situ and modelled values. The maximum Anglian deviation, shown to be in highly turbid waters, is in the vicinity of the Southern data maximum deviations and this may indicate SPM effects in these waters too.

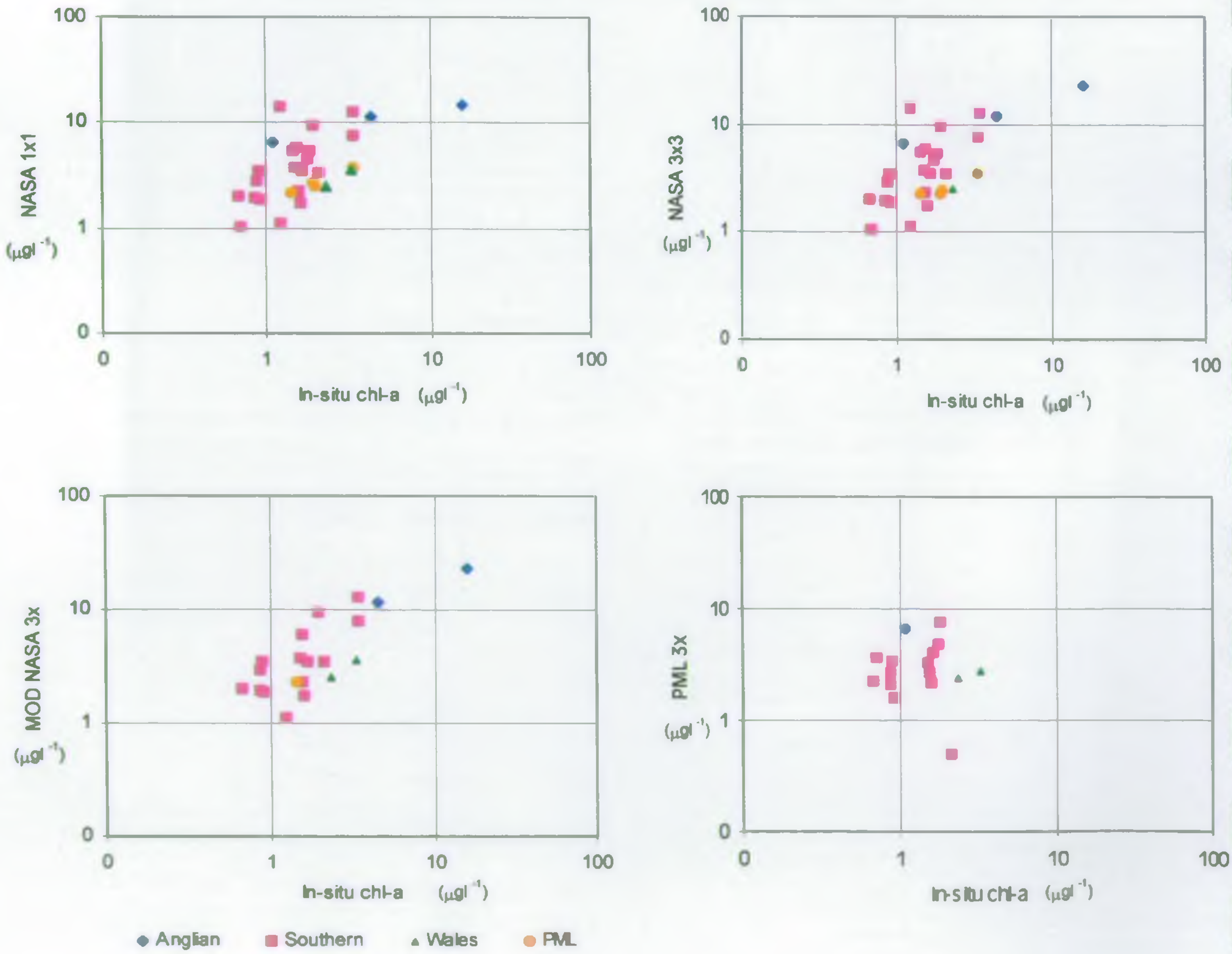

Figure 4. Regional comparisons of algorithms.

In figure 5 a comparison is made between algorithm prediction and time of year. Data collected in August (Wales data) form the best correlation, however with only 2 points this is not a representative sample. June and July are also reasonably correlated whereas in April, no match is found.

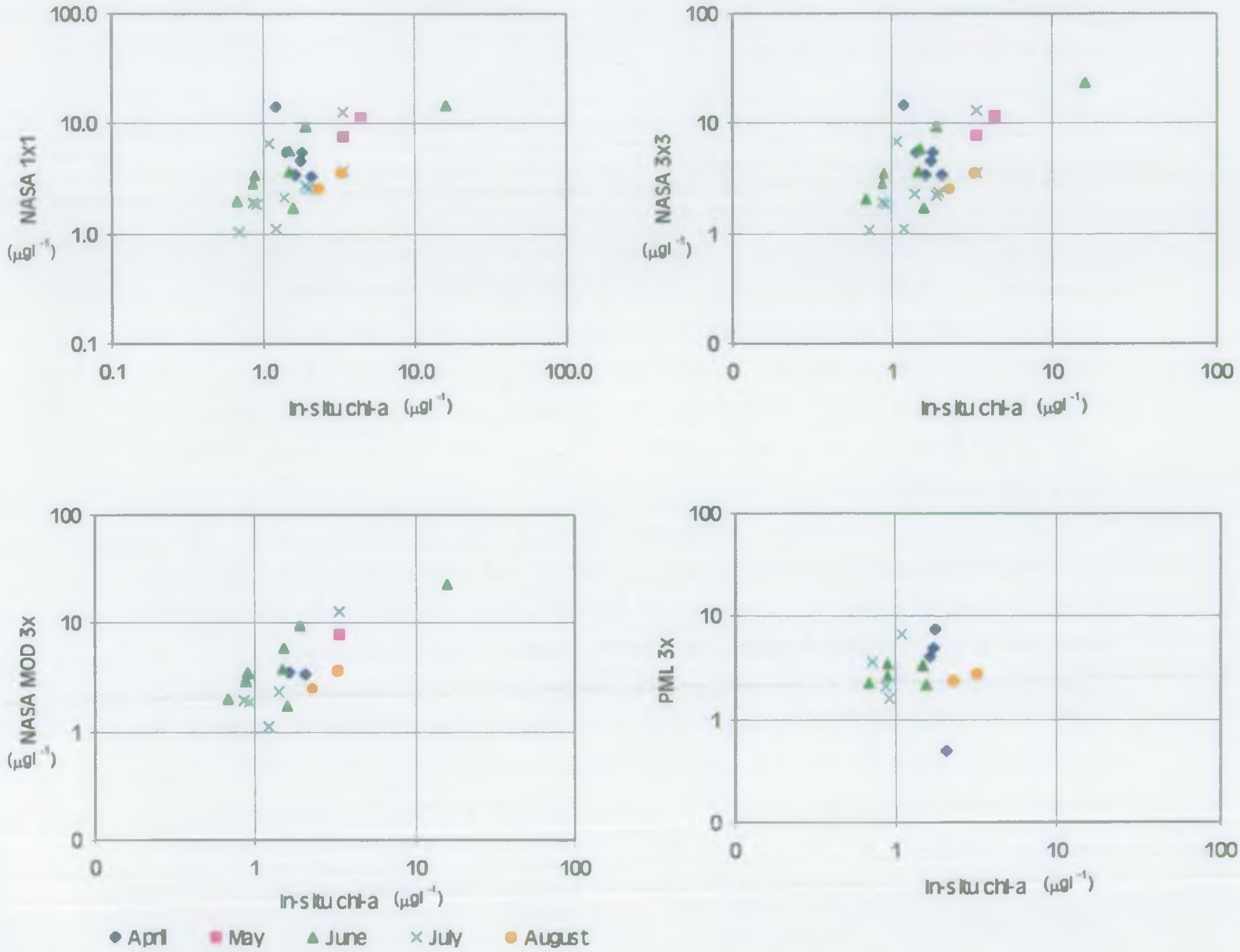

Figure 5. Seasonal comparisons of algorithms.

4.0 Discussion

The SeaWiFS imagery has correlated reasonably well for the NASA and Modified NASA algorithms. These do however appear to improve towards the end of the summer season as riverine, and hence sediment input to the sea reduces. The SeaBAM dataset has provided confidence in the general fit, revealing the exaggeration of the tested algorithms in UK coastal waters. The masking of SPM in the modified NASA algorithm significantly reduces this error giving a 84% correlation which is within the ±35% error margin aimed by NASA. The PML algorithm aims to reduce the effect of SPM and though does reduce the overestimation seen in other algorithms, does not provide any correlation with the limited dataset. It does, however, reduce the level of overestimation. If there had been more *in-situ* measurements, over 5 μgl^{-1}, the PML algorithm could have had greater performance. The entire available dataset, however, has not been analysed due to time restrictions, but it is hoped that further analysis will improve correlations.

Due to suggestive/possible atmospheric influence on bio-optical measurements, the dataset is significantly reduced in the number of *in-situ* points over 10 μgl^{-1}. Such waters are potentially subject to eutrophication and would have been most useful to analyse in correlation. This study is aimed towards using SeaWiFS to monitor the coasts for algal blooms and it is therefore recommended that these datasets are re-evaluated. PML are able to provide measurements of aerosols in the atmosphere. These could be used to indicate more precisely when to discard SeaWiFS data. This may return a large amount of data presently discarded due to uncertainty. It is hoped further analysis will also improve correlation of all algorithms, in particular PML. A larger dataset will also increase the regional and seasonal analysis.

To measure chlorophyll successfully in UK waters using remote sensing techniques, the algorithms clearly need to accurately remove the effect of dissolved sediment, other particulate matter and coloured dissolved organic matter in the surface waters. The OC2v2 algorithm used by NASA has recently been developed further to address this issue (McClain, 2000). The new OC2v4 is aimed to reduce the problems encountered in waters of high latitudes too. Other directions are to use multiple regression or neural networks. Neural networks have recently been applied to SeaWiFS data by Keiner and Brown (1999). They used the 5 SeaWiFS wavebands in training the sample dataset to achieve a correlation of $R^2 = 0.96$ which superseded the NASA algorithm due to its capabilities in Case 1 as well as Case 2 waters.

Focus also lies with atmospheric correction of SeaWiFS imagery. This has been improved with the new SeaAPS 4 software at PML (correspondence with S. Lavender, 2000). Since approximately 90% of the raw signal is attributed to atmospheric factors, the updated version may have a significant impact on algorithm performance.

Errors are as likely to originate from the type of *in-situ* data as from the algorithms. Wernand *et al.* (1998) note that single point measurements are insufficient in the coastal zone where there can be significant changes in particulate and dissolved matter, both temporally and spatially. SeaWiFS averages over a 1 km^2 area and may record up to a difference of several hours from the *in-situ* measurement. It could therefore be more appropriate to shift the emphasis away from algorithm development and instead towards measuring *in-situ* temporal/spatial averages to match that of SeaWiFS. This could use either a collection of constant buoy or repeated track measurements.

Alternatively, future considerations could include other ocean colour sensors, for example the Ocean Colour Monitor (OCM) on board OCEANSAT 1 (Indian), which measures at a higher resolution of 350m. OCM has global coverage and matches the SeaWiFS spectral bands to within ± 3nm. OCM is, however, relatively 'young', only in orbit since May 1999. Other sensors currently available to measure bio-optics in UK waters are shown in table 4, the lower portion of which shows scheduled sensors. These have repeat coverages of 1-4 days; and varying number of bands, *e.g.*, the Multi-angle SpectroRadiometer (MISR) has a high 250m resolution but only 4 bands measures radiance in 4 bands, inadequate for chlorophyll algorithms.

Current Satellite Ocean Colour Sensors

Sensor	Agency	Satellite	Operating Dates	Swath (km)	Resolution (m)
MOS	DLR (Germany)	IRS P3 (India)	March-99	200	500
SeaWiFS	NASA (USA)	Orb View-2 (USA)	August-97	2806	1100
OCM	ISRO	IRS-P4	Launched May-99	1420	350
MODIS	NASA (USA)	Terra (USA)	Launched December-99	2330	1000
MISR	NASA (USA)	Terra (USA)	Launched December-99	360	250
OSMI	KARI (Korea)	KOMPSAT (Korea)	Launched December-99	800	850

Scheduled Satellite Ocean Colour Sensors

Sensor	Agency	Satellite	Launch Date	Swath (km)	Resolution (m)
CHRIS	ESA (Europe)	ERS-3	2001 (data by April)		25
MODIS-FMI	NASA (USA)	Aqua (EOS-PM1)	December-00	2330	1000
MERIS	ESA (Europe)	ENVISAT-1 (Europe)	June-01	1150	300/1200
GLI	NASDA (Japan)	ADEOS-2 (Japan)	November-01	1600	250/1000
POLDER-2	CNES (France)	ADEOS-2 (Japan)	November-01	2400	6000
S-GLI	NASDA (Japan)	ADEOS-3 (Japan)	March-03	1600	750
OCTS	CNSA (China)	Hai Yang-1 (China)	2001-2003	1400	1100

Table 4. Current and scheduled satellite ocean colour sensors with coverage of UK waters (taken from IOCCG, 2000)

One sensor of particular interest to high resolution imaging is the Compact High Resolution Imaging Spectrometer (CHRIS), with a resolution 45 times as accurate as SeaWiFS - 25m.

Due for launch in early 2001, CHRIS will not have global coverage but will instead be used over 15 test sites, one of which includes Plymouth Sound (correspondence with S. Lavender, 2000). The others are distributed globally, for both land and ocean applications. CHRIS will pass over Plymouth Sound 5 times during one day of each month, over duration of the one year study period.

5.0 The Way Forward

Table 5 summarises factors that may have influenced correlation in this study. These include spatial and temporal resolution of both SeaWiFS and *in-situ* data, number in dataset, additional *in-situ* water quality measurements and aerosol data availability. In view that all these have been limited to some extent in this study, yet there is still good correlation in the modified NASA algorithm, the possibility for improved accuracy in future studies of this, or other data, is foreseeable.

	Measurement	In this study	Improvements / Possibilities
1.	Spatial resolution of sensor	1100m	>25km, other satellites
2.	Temporal resolution of sensor	Relies on SeaWiFS only, <4 per day	Use of all ocean colour satellites
3.	Spatial/temporal resolution of *in-situ* data	Spot measurements	Continuous track/buoy measurements
4.	Number of measurements	10% of available data	Use all
5.	Masking through SeaWiFS channels	670 nm only used due to limited data left otherwise	555 and 670 nm with larger dataset
6.	Turbidity / SPM /CDOM measurements	Limited to ~25% of data	Retrieve more matching data
7.	Aerosol measurement	None	Buy from PML

Table 5. Quality of results

To provide confidence in these assumptions, a short 'look see' study could be of value. This would provide a comparison between:

- a small set (3-10) of *in-situ* measurements, to include calibrated turbidity and/or SPM or CDOM - if possible to be measured repeatedly and/or to include several points within 1 square kilometre
- a cloud free SeaWiFS image with all previous products as well as aerosol data
- CHRIS image (not available until 2001)
- any other available ocean colour image from which chl-*a* may be derived, in particular MOS, OCM and MISR (all <500m resolution)

On the basis of the short study's success, further analysis could then proceed.

Following the end of the Coastal Zone Colour Scanner (CZCS) in 1986, bio-optical satellite imagery lay dormant until 1996 after which, a new generation of sensors came into orbit. Consequently there has been limited evaluation of these sensors, with less than 3 years of data available for SeaWiFS. The accuracy will almost certainly improve, through algorithm development and improved atmospheric correction. *In-situ* data, which is required for validation or correlation, will also become better understood as research progresses.

6.0 References

Groom, S. (2000) *Personal communication with S.Lavender, Plymouth Marine Laboratories.*

Habbane, M., Dubois, M.I., El-Sabh, M.I and Larouche, P. (1998) Empirical algorithm using SeaWiFS hyperspectral bands: a simple test. *Technical note, International Journal of Remote Sensing*, 19(11), 2161-2169.

Kahru, M. and Mitchell, B.G. 1999. Empirical chlorophyll algorithm and preliminary SeaWiFS validation for the California Current. In *International Journal of Remote Sensing*, Vol. 20(17), No. 3, pp 423-3,429.

Keiner, L.E. and Brown, C.W. 1998. Estimating chlorophyll concentrations with neural networks. *International Journal of Remote Sensing*, Vol. 20(1), pp 189-194.

McClain, C. 2000. *SeaWiFS data users, email*

O'Reilly, J.E., Maritorena, S., Mitchell, G., Siegel, D.A., Carder, K.L., Garver, S.A., Kahru, M. and McClain, C. 1998. Ocean colour chlorophyll algorithms for SeaWiFS. In *Journal of Geophysical Research*, Vol. 103(C11), No. 24, pp 937-24,953.

Wernard *et al.* 1998. Evaluation of specific semi-empirical coastal colour algorithms using historic datasets. In *Aquatic Ecology*, Vol. 32, pp 73-91.

IOCCG (2000) *Website* http://www.ioccg/sensors

Provision of SeaWiFS Imagery in near real time to Regional representatives to allow for the early detection and monitoring of algal blooms developing offshore

1.0 Introduction

The National Centre for Environmental Data and Surveillance (NCEDS) considered that the collection of earth observation data, specifically SeaWiFS ocean colour imagery, in real time would allow the Environment Agency to address one of the major variables in coastal water quality: the presence of algal blooms. Previous attempts to establish the presence and development of algal blooms using Compact Airborne Spectrographic Imager (CASI) data concluded that the collection of satellite data would be more appropriate. Satellite data allow a daily assessment of a large part of the coastal zone and extend offshore to regions where blooms are more likely to be developing.

Access to real time daily SeaWiFS data would allow the presence of blooms to be established enabling a system to be developed to warn Regional Water Quality staff of the presence of potentially harmful blooms in their coastal waters. Further data collection using the Agency's CASI and survey vessels could then be put into place. This may take the form of toxicity studies or the imposition of beach or shellfisheries warnings. It was therefore considered imperative that data be analysed in near real time as opposed to sue of an archived product.

1.1 The Sea-viewing Wide Field-of-view Sensor (SeaWiFS)

The Sea-viewing Wide Field of View Sensor (SeaWiFS, NASA) was launched in August 1997, by Orbital Sciences Corporation aboard the OrbView-2 satellite. SeaWiFS is designed to measure ocean colour, the spectral variation of water leaving radiance that can be related to concentrations of phytoplankton pigments, coloured dissolved organic matter and suspended particulate matter (Hooker et al, 1992).

The SeaWiFS sensor records the water leaving radiance at eight wavebands centred at 412, 443, 490, 510 and 555, 670, 765 and 865 nm. Data are collected at both full coverage, with a pixel size of 1.1 km and global area coverage, with a pixel size of 4 km.

2.0 Data dissemination system

A system has been established to receive SeaWiFS imagery from the NERC satellite data facility at Plymouth Marine Laboratory (PML). These data are collected by the NERC Satellite Receiving Station at Dundee and passed for processing to products at PML using the SeaWiFS Automatic Processing System (SeaAPS). The products obtained from PML initially were chlorophyll-a concentration, water-leaving radiance at 555nm and a true colour composite image comprised of data at 555nm, 510nm and 443nm. A further channel, water-leaving radiance at 670nm, was provided by PML after June.

Purchase of SeaWiFS data in near real time required payment of commercial rates. However, NASA has identified the need for the supply of real time data in research applications and provides a limited number of real time licences for approved research projects. The National Centre made a successful application to NASA for the use of these data with approval being given in April 1999 for real-time access for a period of six months from 1 May to 31 October 1999.

Prior to the commencement of data collection, the National Centre notified all Regional Water Quality managers and Regional Environmental Protection managers of its intention to supply SeaWiFS data via the internal e-mail system. These managers were asked to either receive the data themselves, or to nominate a representative within their team to do this. A full list of the recipients of SeaWiFS data may be found in Appendix A. This includes other members of the Environment Agency who independently expressed interest in receiving the data during the project.

Data were received from PML on a daily basis, usually within four hours of the satellite overpass. These data were downloaded from the PML anonymous ftp site and stored on the network drives at the National Centre. Data underwent a series of processing stages, described in section 3. Before being distributed to the regional representatives, the data were subject to certain criteria before being sent out (see table 1)

Parameter	**Criteria**
Cloud Cover	Only chlorophyll-*a* images that had significant water areas clear of cloud were passed to the regions. During periods of prolonged cloud cover images with the least cloud were sent.
Chlorophyll Levels	Any images showing significant levels of chlorophyll-a offshore and onshore were provided to the regions
Water Features	False colour composites showing features of interest such as coccolith blooms were also provided along with the chlorophyll-*a* images to the relevant regions
Water Features	False colour composites showing features of interest such as coccolith blooms were also provided along with the chlorophyll-*a* images to the relevant regions
Suspended Sediment	Areas of water containing significant levels of suspended sediment were masked from the chlorophyll-*a* images. The presence of sediment in the water causes the algorithm to return unreliable values of chlorophyll-a.

Table 1. Evaluation criteria of imagery prior to distribution

E-mails were sent out each week to the regional representatives containing a series of the best images from the previous week in JPEG format. The full SeaWiFS chlorophyll image covering England and Wales was sent to each region to ensure nothing of interest in neighbouring regions was removed.

When possible bloom features were seen on the false colour or chlorophyll images copies were sent out next day to the appropriate regions.

3.0 Processing stages

Data were initially received as true colour composite images, including a channel for water leaving radiance at 550nm / 670nm and calibrated chlorophyll-*a* images. The algorithm used to calibrate for chlorophyll-a was a Case 1 type designed for use in open ocean waters. Case 1 waters may be defined as those optically dominated by biological matter, i.e. by the presence of phytoplankton and its associated degradation products (Morel and Prieur, 1977). Waters around the coastline of England and Wales are described as Case 2 waters, defined as water optically dominated by the presence of suspended particulate matter or Gelbstoff. Application of Case 1 type algorithms in areas having high sediment loading results in erroneously high chlorophyll-*a* concentrations. Much research has been carried out in the past 20 years to establish a robust algorithm for the calibration of satellite and airborne ocean colour sensors for chlorophyll-*a* concentration in Case 2 waters. No conclusive algorithm has yet been derived.

The use of remote sensing technology to provide spatial estimates of chlorophyll-*a* concentration has been ongoing since the launch of the Coastal Zone Color Scanner (CZCS) in 1978. Algorithms were developed relying on the absorption properties of chlorophyll-*a*, relating the reflectance measured at blue wavelengths with that from green wavelengths. This technique, which has been used extensively, is commonly referred to as the blue/green ratio method (Gordon *et al.*, 1980).

CZCS data proved unsuitable for estimations of chlorophyll-*a* concentration in the coastal zone, due to its low spatial resolution. Coastal phenomena are often at scales smaller than the 0.825 km square pixel size of the CZCS. Aerial systems combine a finer spatial resolution (dependent on altitude) with temporal flexibility. Algorithms of the form developed for CZCS were therefore applied to data from aircraft systems by a number of workers (for example Moore and Aiken, 1990, Matthews *et al.*, 1992). These were found to be applicable for the site at which the algorithm was developed, but were not portable between sites. This was due to two key interference factors: the intervening atmosphere between the target and the sensor and the presence of suspended sediment.

A further technique for the calibration of high spectral resolution aerial imagery relies on the *in-vivo* fluorescence peak of chlorophyll-*a*. A small percentage of the visible light absorbed by chlorophyll is re-emitted as fluorescent energy after undergoing transition to a higher wavelength. This emission is manifested in the reflectance spectrum as a narrow peak at approximately 685 nm (Neville and Gower, 1977). The exact position of peak has been shown to alter due to the absorption effects of chlorophyll-*a* in this region of the spectrum and to the presence of suspended solids (Matthews, 1994). The height of this peak above a baseline spectrum is directly related to chlorophyll-*a* concentration. This Fluorescence Line Height (FLH) technique alleviated the two problems encountered with the use of the blue/green ratio method in coastal waters identified above. The chlorophyll-a fluorescence feature is narrow, having a bandwidth of approximately 20 nm. The atmospheric effects do not alter greatly around this feature, with no major atmospheric absorption features interfering with the fluorescence feature. Furthermore, the feature occurs in a part of the spectrum where reflectance from water and suspended sediments are low, making the peak more easily distinguishable in areas of high suspended solids loading. The technique was developed further to overcome problems with low signal to noise ratios (Neville and Gower, 1977 and Gower and Borstad, 1981).

The use of the FLH technique in the UK coastal waters, however, has not always proved successful, with a combination of high concentrations of suspended particulate matter and high chlorophyll-*a* concentrations resulting in erroneous estimates (Environment Agency, 1997). This may be due to the varying position of the fluorescence peak which has been noted in fresh waters (Gitelson, 1990) and in laboratory simulations of coastal waters (Matthews, 1994). The coarse spectral resolution routinely offered by remote sensing systems, even those flown on airborne platforms, acts to smooth the effect of the peak, decreasing the correlation with chlorophyll-*a* concentration. Collection of high spectral resolution data will allow the presence of spectral features due to chlorophyll-a within the reflectance spectra to be identified at the algorithm development stage.

The Environment Agency carried out research in 1996 into the development of algorithms for the estimation of chlorophyll-*a* concentration from airborne imagery (Matthews *et al.*, 2000). This research showed that estimates of chlorophyll-*a* concentration could be made with only limited *in-situ* data using the FLH technique. No global algorithm could however be produced which could be applied in retrospect to data collected during the National Coastal Baseline Survey. Moreover, the need identified above to collect data over wide spatial scales precludes the use of the FLH technique. This is unsuitable for current satellite payloads as the required spectral wavebands are unavailable.

Work carried out by PML has shown that the application of the NASA Case 1 algorithm to SeaWiFS data gives good results in areas where sediment concentrations are low. An indication of the presence of high suspended sediment may be gained from investigation of the water leaving radiance at 550nm and 670 nm. Suspended sediment causes a peak in radiance at these wavelengths.

NCEDS has therefore developed a differencing algorithm to mask those areas in the chlorophyll-*a* images where scattering by particulates is high. DN values of both water leaving radiance (S) and chlorophyll-a (C) were used in the following logic statement to create a new image (N) with regions of high SPM (black) and cloud / land (grey) masked out.

```
If ((C >=1 and C<255) and (S <10 and >0)) then N = C

Else if (C = 255 and S = 255) then C = 255 (white)
Else if (C = 0 and S = 0) then N = 1 (grey)
Else N = 0 (black)

End if
```

Figure 1 shows an extract of a SeaWiFS images where erroneously high chlorophyll-*a* concentrations may be found. Figure 2 shows the effects of applying the sediment mask to this dataset. Although this results in the loss of data it provides a more robust tool for the investigation of true chlorophyll-*a* concentration.

Figure 1. Extract of SeaWiFS imagery where erroneously high chlorophyll-a concentrations may be found

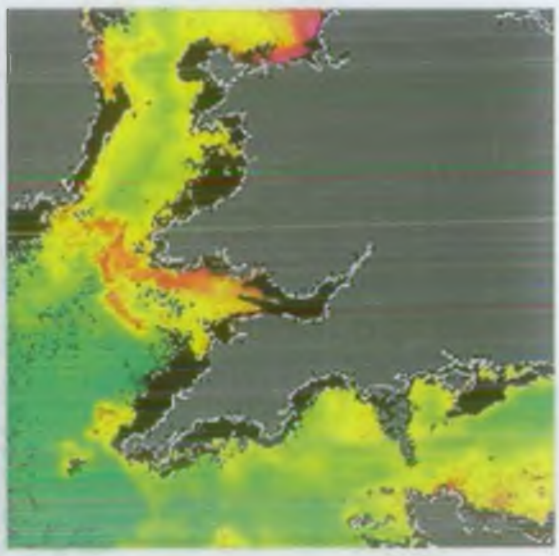

Figure 2. SeaWiFS imagery after applying the sediment mask (shown in black). Grey areas represent clouds and land.

During the data collection period the NCEDS and Plymouth Marine Laboratory worked together to produce an improved algorithm for the measurement of chlorophyll-*a*. None of these experimental algorithms were applied to the data sent to the Regions, but the results of the analysis are included in the preceding reports.

4.0 Application of the data

During the data collection period, a number of users expressed a great interest in the data. The standard product supplied to the Regions was a SeaWiFS image of the entire coastline (excluding the far north-east coast). Those users who required more spatially or temporally detailed information were able to gain this from the National Centre, for example on daily basis and for a specific Regional coastline. Equally, data that showed levels of cloud cover considered too great for blanket distribution could be supplied to users who expressed a specific interest.

Essentially SeaWiFS data provided a daily picture of potential bloom events around the coastlines of England and Wales. The imagery were used by the various regions to verify the presence of reported algal blooms and assess their extent and duration. A particularly good example comes from a bloom event detected in the English Channel, in July 1999.

The National Centre received SeaWiFS imagery (dated 24 July) which showed a clear coccolithophore bloom (*Emiliania huxleyi*) in the true colour composite image (Figure 3). The chlorophyll-*a* image also showed high levels although some areas were masked as sediment due to the high scattering level of the coccolithophores (Figure 4).

Figure 3. SeaWiFS true colour composite dated 24th July 1999, showing a clear coccolithophore bloom off the SW coast.

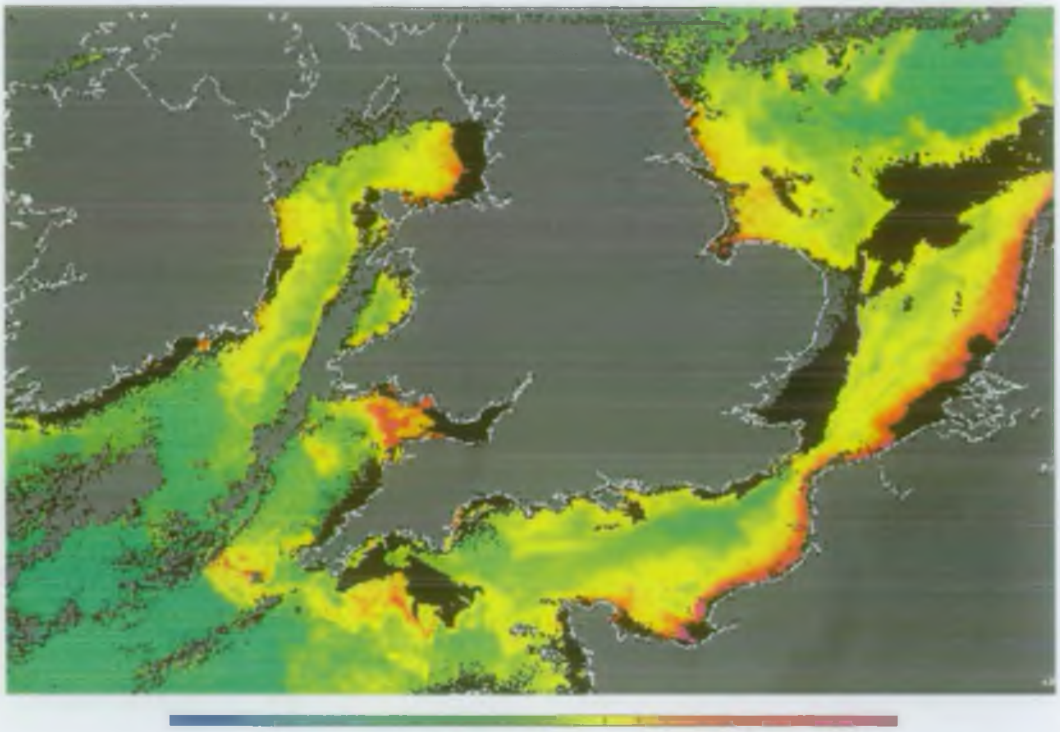

Figure 4. SeaWiFS chlorophyll-a map derived using the NASA 2v2 algorithm, with regions apparently high in sediment masked out in black and regions of cloud or land in grey.

The National Centre were also contacted by south-west Region about a red tide of *Alexandrium tamarense* in the Fal Estuary. The National Centre therefore mounted a CASI data collection campaign to cover both of these events on 27 July. The CASI true colour composite imagery clearly showed the presence of red algae in the Fal Estuary and the presence of the coccolithophore bloom further offshore impacting upon the entrance to the estuary (Figures 5 and 6).

Water samples for algal analysis were collected by Plymouth Marine Laboratory within the coccolith bloom and by south-west Region within the Fal Estuary for the *Alexandrium*. These data are being used to calibrate the CASI and SeaWiFS imagery as part of the collaborative research project with PML, which will be reported on later.

The imagery has also been used to assist with the interpretation of 'ground truth' data as the imagery provides a wider picture of bloom events due to its spatial coverage. These data can then be compared to historical data sets to investigate both seasonal and long term trends, for use in eutrophication studies.

Figure 5. CASI true colour composite showing the presence of red algae in the Fal Estuary

Figure 6. CASI true colour composite showing the coccolithophore bloom seen in the SeaWiFS imagery, impacting off-shore from the Fal Estuary.

6.0 Discussion and Recommendations

It seems from the responses given, that future use of SeaWiFS data will be as an additional source of information as opposed to a reactive tool. This is due to two factors, firstly the limited coverage of the near shore region (<1km from the coast) due to the low spatial resolution of SeaWiFS. The second factor is the uncertainty in determining accurate chlorophyll-*a* concentrations in coastal waters dominated by the presence of dissolved organic matter (DOM) or suspended sediment, or both (Case 2 waters). The algorithm used operationally was the NASA OC2v2 designed for use in Case I waters, described as those optically dominated by biological matter. This results in an over-estimation of chlorophyll-*a* concentration levels, hence limiting the use of the data. Either these limitations need to be better defined or more robust algorithms suited to Case 2 waters need to be found.

The images provided to the regions allowed for individual bloom events to be detected offshore, albeit with limited confidence, thereby providing an early warning to the regions. However if the use of satellite data is to become an operational tool for coastal monitoring, more information needs to be given on where and when a bloom may come ashore. This type of prediction will require additional inputs from historical data and model data on how and when bloom events occur and any transport mechanisms imposed on them.

It is anticipated that as new sensors become operational and algorithms more suited to case II type waters are developed, these problems will be over-come, thereby paving the way for operational use of space borne sensors to monitor coastal zone water quality. As an example, the Moderate Resolution Imaging Spectrometer (MERIS, ESA) due for launch in June 2001, has approximately the same resolution as SeaWiFS but with two additional channels in the red region. These should provide greater accuracy in determining parameter retrieval such as chlorophyll-*a*, in Case II waters (Cipollini and Corsini 1996). Experimental satellites are also being developed with the capability for higher spatial and spectral resolutions, thereby facilitating the development of more accurate algorithms for use in coastal waters. For example CHRIS (Compact High Resolution Imaging Spectrometer) due for launch in early 2001 has a spatial resolution of 25m and up to 18 wavebands compared to 1.1km and 8 wavebands for SeaWiFS.

6.0 References

Cipollini, P. and Corsini, G. 1996 SeaWiFS and MERIS: a comparison of their performance for the estimation of optically active components in ocean water. In *IGARSS '96 : Remote Sensing for a Sustainable Future, IEEE*, Vol. 2, pp 827-1402

Environment Agency. 1997. Calibration of CASI imagery for high concentrations of chlorophyll-*a* in turbid waters. Internal Report, National Centre for Environmental Data and Surveillance.

Gitelson, A. 1990. The peak near 700 nm on radiance spectra of algae and water: relationships of its magnitude and position with chlorophyll-*a* concentration. In *International Journal of Remote Sensing*, Vol. 13, No. 17, pp 3367-3373

Gordon, H.R., Clark, D.K., Mueller, J.L. and Hovis, W.A. 1980. Phytoplankton pigments derived from Nimbus-7 CZCS: Initial comparisons with surface measurements, In *Science*, 210, p63

Gower, J.F.R. and Borstad, G. 1981. Use of in-vivo fluorescence line at 685 nm for remote sensing surveys of surface chlorophyll-*a*. In *Oceanography from Space*, edited by J.F.R. Gower. New York: Plenum Press, pp 329-338

Hooker, S.B., *et al.* 1992. SeaWiFS technical report series, Vol 1, An overview of SeaWiFS and ocean colour. NASA technical memorandum 104566, 1, 25 pages.

Matthews, A.M., Wernand, M.R. and Boxall, S.R. 1992. Observations of a coastal front from remotely sensed imagery. In *Ocean Colour: Progress in Studies of Oceanographic Processes, James Rennel Centre for Ocean Circulation*, January 1992.

Matthews, A.M. and Boxall, S.R. 1994. Novel algorithms for the determination of phytoplankton concentration and maturity. In *Proceedings of the Second Thematic Conference on Remote Sensing for Marine and Coastal Environments*, New Orleans, January 1994.

Matthews, A.M., Duncan, A.G. and Davison, R.G. 2000. An assessment of calibration techniques for estimating chlorophyll-*a* concentrations from airborne multispectral imagery, In *International Journal of Remote Sensing* (pending).

Moore, G. and Aiken, J. 1990. Aircraft multispectral remote sensing of water colour off Helgoland. In *Applications and Developments in Imaging Spectrometry: Proceedings of a Remote Sensing Society Workshop*, 20th November 1999, pp18-31

Morel, A. and Prieur, L. 1977. Analysis of variations in ocean colour, *In Limnology and Oceanography*, Vol. 22, pp 709-722

Neville, R.A. and Gower, J.F.R. 1977. Passive remote sensing of phytoplankton via chlorophyll-*a* fluorescence. In *Journal of Geophysical Research*, Vol. 82, No. 4, pp 3487-3493

Appendix A: SeaWiFS recipients

Contact Name	Position	Replied ?	Further Interest?
Ian Adams	Regional Water Quality Manager – Thames		
→ Andrzej Nowosielski	Water Quality Planner – Thames	By email	Yes
David Brain	Groundwater National Centre		?
Clive Gaskell	Regional Water Quality Manager – NW	By email	Yes
Tony Warn	Environmental Quality Manager - HO Bristol	By phone	
Michael Manderville	Senior WQ Planning Officer - Southern	By phone	
Peter Jonas	Senior Scientist – SW	By phone	Yes
Martin Booth	Regional Environmental Protection Manager – SW	By phone	
Jane Cecil	Area Fer Manager – Southern	By phone	
Jeremy Frost	Regional Environmental Protection Manager - NW		?
John Harrison	Environmental Protection Manager - Welsh		?
Dr. Mick Pearson	Regional Environmental Protection Manager - Anglian	By phone	
Andrew Skinner	Regional Environmental Protection Manager - Midlands	By phone	
Peter Jones	Senior Scientist – North West	By phone	Yes
Mike Best	Regional Marine Officer – Anglian	By phone	Yes
John Orr	National Marine Service – Anglian		?
Sarah Peaty	Marine Science Ecology Team Leader - NE	By email	Yes
Christa Upjohn	Scientific Officer – SW	By phone and email	Yes
→ Duncan Struggles	Biologist – SW		
→ Andy Haigh	Biologist – SW	By email	Yes
→ Andy Hicklin	Project Officer (LM's) – SW		
→ George Green	Team Leader Biology – SW		
→ Rob Moore	Senior Scientist (QA) – SW		
John Broughton	Water Quality Scientist – North East		Yes
Dave Lothian	Regional Scientist / Marine Sect Base Hd	By phone	Yes