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The ABDMAP (Algal Bloom Detection, Monitoring and Prediction) Concerted Action

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Abstract. This paper describes the ABDMAP (Algal Bloom Detection, Monitoring And Prediction) project, which was a Concerted Action funded by the European Commission and carried out from April 1997 to March 1999. In the course of the project a number of workshops were held in various European countries. These workshops were devoted to various scientific aspects of algal blooms and, in particular, to the use of Earth observation (remote sensing) data for the study of such blooms. Great attention was given to the needs of users or potential users from the academic and research communities, from organizations with operational responsibilities for the introduction of legislation or for the monitoring of algal blooms. A state-of-the-art review of scientific knowledge and of applications of this knowledge was compiled and a number of actions were undertaken to widen the appreciation of the potential use of Earth observation (remote sensing) data for the study of algal blooms, including toxic algal blooms.

1. Introduction

1.1. *The ABDMAP project*

ABDMAP (Algal Bloom Detection, Monitoring And Prediction) was a Concerted Action funded by the European Commission, DGXII (Contract Number: ENV4-CT96-0355). It was related to the Centre for Earth Observation (CEO) Programme of the European Commission and the declared objective of the CEO to increase the use of Earth observation (remote sensing) data. A Concerted Action is not itself intended to involve carrying out a research programme, but rather its aim is to bring together scientific research and to enable a greater understanding of users' information needs. In the case of ABDMAP, this involved enabling the potential role for remote sensing data to be better understood by those actively involved in monitoring algal blooms. ABDMAP brought together both scientists and those statutory bodies with an interest and role to play in the monitoring of algal blooms and toxins.

Algal blooms occur in a wide variety of locations throughout Europe, as well as globally, and their occurrence is increasingly being reported. Apart from their intrinsic

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scientific interest, their importance lies in the fact that many of these blooms are toxic, and so have an impact upon:

- shellfish and fin fish industries;
- tourism;
- human health.

Recent events have reinforced concerns that anthropogenic sources are having a significant effect upon the water quality in our coastal environment and in inland water bodies. Not only is detection and monitoring essential, but further advances are also required in the prediction of algal blooms. This project was concerned primarily with algal blooms in the sea rather than in inland water bodies.

Local, regional, and national bodies (e.g. Environmental Protection Agencies, Environmental Health Organizations and Agriculture & Fisheries Departments) have a role to play in the detection and monitoring of toxic algal blooms. Traditionally, this duty has been undertaken through a series of *in situ* monitoring programmes (typically at shellfish production sites, and also sites of previous blooms) with increasing frequency at the main algal bloom season. Remote sensing has the potential to provide greater spatial coverage, greater temporal coverage and additional environmental information.

The use of Earth observation data from satellites to monitor algal blooms has to be regarded as experimental rather than operational. Earth observation data will not be able to answer all the questions that may be asked, but the data have a clear role when used in conjunction with other data sources in the detection, monitoring and (potentially) prediction of algal blooms.

End users of the potential information to be obtained from Earth observation data in the context of ABDMAP were involved throughout this Concerted Action, with local end users being encouraged to participate in each of the project workshops involved in the Concerted Action.

A number of different categories of customers or end users have been identified including:

- academic research
- operational research
- operational monitoring
- long-term trend evaluation
- commercial
    - local scale—e.g. councils, fish farmers, tourism
    - national—the Government
- Financial/insurance sector
    - risk assessment
- The media
- Policy makers/law makers

1.2. *Objectives*

The aim of this Concerted Action was to bring together leading scientists and researchers, both from the collaborating partners and others, to consider the present use and future possibilities for the use of Earth observation (EO) data in this field.

Through the close involvement of end users over the period of the Concerted Action, this project sought to stimulate the uptake of EO data as a key information source in the detection, monitoring and prediction of algal blooms in European marine waters. It is hoped that this close working will lead to an algal bloom information system to be designed/specified (i.e. not implemented but planned) reflecting the user needs, and the capabilities of the latest EO technology and scientific advances.

The objectives of the ABDMAP Concerted Action were as follows.

(*a*) To study the present status and the potential for future development of models for predicting the appearance of algal blooms.
(*b*) To study the relative importance of the various factors contributing to the onset of blooms, and thence the relative importance of the various parameters in the models, and the extent to which remote sensing (EO) data can contribute to the provision of values of these parameters to enable predictions of the onset of blooms to be made.
(*c*) To advance the ability to detect and identify algal and cyanobacterial blooms, incorporating the use of remote sensing (EO) data, specifically including toxic blooms.
(*d*) To use this knowledge to formulate the requirements of future research programmes targeted to address specific problems identified through the Concerted Action.
(*e*) To increase the knowledge base and dissemination of research results through sharing advances and breakthroughs made in a series of workshops by publishing the reports of the workshops.
(*f*) To make recommendations to policy makers such as the European Environmental Agency and the European Commission concerned with water quality matters, and to ensure their directives and recommendations recognize the European perspective.

Typical questions raised by ABDMAP were the following.

- Is it possible to use EO data to *predict* the appearance of an algal bloom?
- Is it possible to use EO data to *detect* a bloom?
- Is it possible to use EO data to *identify the biological species* present in a bloom?
- Is it possible to use EO data to *monitor the evolution* of a bloom?

1.3. *The ABDMAP consortium*

The project team for this Concerted Action comprised eight partners from across Europe. Their expertise is summarized in table 1.

1.4. *Outline of the methods used*

The ABDMAP Concerted Action was implemented through a series of six thematic and regional workshops in various European countries, along with a number of supporting measures including end user consultation, the development of a metadatabase and completion of a state-of-the-art review. ABDMAP ran for two years from April 1997 to March 1999, along with a follow-up review workshop in May 1999. The series of workshops held throughout Europe conducted within ABDMAP is summarized in table 2. Each workshop addressed a particular aspect of algal bloom detection, monitoring and prediction and also focused on a particular region within Europe. These workshops were intended to draw audiences from a wide range of

Table 1. Partners in the ABDMAP consortium.

Name	Country	Expertise	Role
University of Dundee	Scotland	Remote sensing, marine and aquatic blooms, toxins	Coordinator, metadatabase & Dundee workshop
University of Wales, Bangor	Wales	Marine optics, remote sensing, biophysical monitoring	Bangor workshop
Kiel University	Germany	Eutrophication	Kiel workshop
Istituto Superiore di Sanita	Italy	Toxic algae, public health	Rome workshop
Stockholm University	Sweden	Remote sensing, cyanobacteria	Stockholm workshop
Ecole des Mines de Paris	France	Eutrophication	French workshop
Université du Littoral	France	Coastal water quality	French workshop
Institute of Marine Biology of Crete	Greece	Impact on fisheries	Iraklion workshop

Table 2. The workshops in the ABDMAP project.

Dundee, May 1997	Workshop 1, ABDMAP Overview
Kiel, September 1997	Workshop 2, Algal bloom monitoring, anthropogenic and natural causes
Rome, April 1998	Workshop 3, Public Health
Stockholm, June 1998	Workshop 4, Detection, monitoring and identification
Iraklion, Crete, September 1998	Workshop 5, Earth observation data and products for inputs to biological models
Wimereux, France, March 1999	Workshop 6, Détection des blooms d'algues: ABDMAP (Algal Bloom Detection, Monitoring and Prediction)
Bangor, Wales, May 1999	Review Meeting & Workshop 7, ABDMAP review and focus on the Irish Sea

organizations including academia, research and those bodies with a statutory obligation to monitor algal or phytoplankton blooms. The workshops and their conclusions will be described later (see §5).

The other main features of ABDMAP included the use of an end user questionnaire, the development of a metadatabase, compilation of a state-of-the-art review and description of the project through presentations at a number of international fora. End users' needs for greater understanding of the capabilities and potential of EO data have been addressed throughout the ABDMAP workshops and through the state-of-the-art review. The ABDMAP metadatabase should aid the location of data for algal bloom detection and prediction.

Through the workshops and the end user questionnaire it was hoped that an appreciation of the potential cost effectiveness of EO data from the end users' perspective would be gained. It is, however, recognized that EO data alone will not provide all the information required by end users in this field.

2. Introduction to algal blooms

Research into the causes and development of algal blooms incorporates numerous techniques and disciplines in the aim of furthering our knowledge about such events. Research can include laboratory analysis, incorporating techniques such as microscopy or chromatography into field work, or even studies of vast areas obtained through satellite imagery. All of these disciplines and techniques combined provide a greater level of information to the research concerning a bloom event than a single discipline alone.

The ABDMAP Concerted Action was particularly concerned with establishing and hopefully expanding the role of EO (remote sensing) in algal bloom prediction and monitoring. The role of EO data in such activities and its future potential was emphasized, where the wide synoptic coverage afforded by remote sensing can help further knowledge of the distribution of suspended sediments, circulation patterns around variable coastlines, and of the production of such regions through the mapping of chlorophyll concentrations (including algal blooms).

2.1. *Health issues*

Toxic algal blooms can occur in fresh, brackish and marine waters causing health problems to both humans and animals alike. There are various health issues associated with more than 60 identified toxins of cyanobacteria which are regarded as neurotoxins, hepatotoxins, cytotoxins, skin irritants and gastrointestinal toxins. These categories are entirely appropriate for the anatoxins and cyanobacterial paralytic shellfish poisoning (PSP) toxins. Antoxin-*a* and the more recently identified methylated form, homoanatoxin-*a*, are postsynaptic cholinergic nictoine agonists which act as neuromuscular blocking agents. These alkaloids cause staggering, gasping, muscle fasciculations and cyanosis in animals, plus opisthotonus in birds, with death by respiratory arrest. The guanidine methyl phosphate ester, anatoxin-*a*(s), is a potent inhibitor of chloinesterases. It causes hypersalivation, lacrymation, diarrhoea and ataxia with rapid death in domestic animals. The potent hepatotoxins, microcystins and nodularins cause severe disruption of liver architecture and function; clinical signs include weakness, recumbency, pallor, vomiting and diarrhoea. Death occurs due to pooling of blood in the liver and respiratory arrest. Cylindrospermopsin, a crytotoxic guanidine alkaloid, is an inhibitor of protein synthesis and causes necrotic injury to the liver, kidneys, adrenals, lungs and intestine. Skin-irritatory toxins include tumour-promoting protein kinase activators (Codd 1998).

One division of the marine microalgae is the dinoflagellates group, of which a number of species produce substances that act as neurological toxins in humans. Dinoflagellates form part of the base of the marine food chains, which are fed on by shellfish and in turn humans. Two groups of poisonings by these toxins have been identified: (1) diarrhoeic shellfish poisoning (DSP), which causes gastro-intestinal problems but no serious effects (except there is recent evidence that the toxins promote tumours), and (2) the more potent PSP, which in extreme cases causes death due to respiratory paralysis (Kelly and Hallegraeff 1992).

Toxins enter the food chain as the phytoplankton are filtered from the water as food by shellfish such as clams, mussels, oysters, or scallops, which gradually accumulate the algal toxins eventually reaching levels that are potentially lethal to humans or other consumers. The first recorded case of a human fatality due to poisoning through eating shellfish contaminated with algal toxins happened in 1793, when Captain George Vancouver and his crew landed in British Columbia in an area now known as Poison Cove. He noted the local Indian tribes also refused to eat shellfish when the seawater became phosphorescent due to dinoflagellate blooms. On a global scale, approximately 2000 cases of human poisoning (fatal in 15% of the cases) through fish or shellfish consumption are now reported each year. Poisoning syndromes have been given the names paralytic, diarrhoeic, neurotoxic, and amnesic shellfish poisoning (PSP, DSP, NSP and ASP) according to their various manifestations. A fifth human illness, ciguatera fish poisoning (CFP), is caused by biotoxins produced by epibenthic dinoflagellates attached to surfaces in many coral reef communities. If not controlled, the economic damage through reduced local consumption and reduced export of seafood products can be considerable.

Table 3 (from the work of Codd (1998)) shows some possible causes of cyanobacterial toxin exposure in fresh, brackish and marine waters, plus the relevant activities associated with the activity in each case. Examples of toxic poisoning of shellfish can be found for locations around the world, including Ireland (Ambrose *et al.* 1998), Argentina (Montoya *et al.* 1998) and New Zealand (Mackenzie *et al.* 1998). Granéli *et al.* (1999) provide a number of references citing incidences of human death from eating fish caught from water bodies infected by cyanobacterial blooms, dog deaths along the Swedish and Finnish coasts and cattle and dog deaths on the Baltic and North Sea coasts of Germany.

Cyanobacteria are not geographically limited to Europe and its surrounding waters. The earliest detailed report of stock deaths came from Alexandria, South Australia, in 1878 (Francis 1878) due to a bloom of *Nodularia spumigena.* This cyanobacterium appears to be particularly responsive to the availability of phosphate in the water and sediments, and is capable of forming massive water blooms in summer (Falconer 1992). The use of phosphatic fertilizers in river catchments and the high phosphate content of treated sewage effluents contribute to the increasing incidence of these water blooms (Lukatelich and McComb 1986). The first recorded toxic dinoflagellate bloom to occur in the Philippines was in 1983. Since then over 2000 PSP cases have been reported, leading to a total of 115 deaths with economic losses estimated to be as high as 10 million PHP (Philippine Pese) for each PSP event.

Table 3. Some possible routes of exposure to cyanobacteria toxins. F, B and M represent fresh, brackish and marine waters respectively (Codd 1998).

Exposure route	Water type	Relevant activity
Skin contact	F, B, M	Recreation, work practices; direct contact with toxic sum and mat material
	F, B, M	Recreation, work practices; direct contact with raw water containing toxic blooms and free toxins
	F	Bathing, showering with treated water containing toxic blooms or free toxins
Drinking	F, B, M,	Accidental ingestion of toxic scum
	F	Drinking of raw water containing toxic blooms or free toxins
	F	Drinking of treated water containing toxic blooms or free toxins
Inhalation	F, B, M?	Showering, work practices, watersports
Food consumption	F, B, M	Consumption of shellfish or fin fish if containing toxins
	F, B?	Consumption of plant products if toxins are accumulated by spray irrigation
Haemodialysis	F	Exposure to dialysis water containing cyanobacterial toxins

2.2. *Economic losses*

Algal blooms can have socio-economic effects in European waters, with losses in revenue from recreation, tourism and aquaculture practices (Lindholm 1998). Incidences of economic losses in European waters include a massive bloom of *Chrysochromulina polylepis* during 1988 in Scandinavian waters leading to heavy losses of farmed fish (Rosenburg *et al.* 1988). Tourism can also be affected, with algal blooms causing large unsightly mucilage to be deposited on beaches along the Adriatic Sea in 1989 resulting in a large decline in tourist numbers for the area for a number of years (Penna *et al.* 1993). In Mexico, 45% of environmental emergencies recorded in 1996 were associated with toxic algal blooms (GEOHAB website). As another example, on the west coast of South Africa, high biomass dinoflagellate blooms are often associated with anoxic events and in some cases the production of hydrogen sulphide. In southern Benguela in 1997, a single event of this type, attributed to the decay of a massive bloom of *Ceratium furca*, was responsible for the stranding of an estimated 2000 tons of rock lobster with a value of 50 million US$ (GEOHAB website). Further examples of economic losses and health problems can be found in the work of Granéli *et al.* (1999).

Non-toxic blooms of microalgae can also result in fish and invertebrate deaths due to oxygen depletion caused by either high respiration rates of the algae or bacterial respiration during decay of the bloom. Mass occurrences of species forming mucilage, for example *Phaeocystis* in the Baltic Sea, can be a serious aesthetic and economical problem in areas used for recreation. It is difficult to assess the full economic losses associated with a harmful algal bloom (HAB) event; either the level of the losses is not made available to the public or the 'knock on' effects are never considered. The loss of markets and tourism are one indication, but the potential collapse of local communities and social structure through a local resource being damaged or destroyed cannot always be fully accounted for.

2.3. *Detection*

Algal blooms may be detected using a range of techniques, including laboratory, field and EO observations. Inevitably the interpretation of remotely sensed data related to algal blooms involves some understanding of basic marine optics. Relevant references which give an overview of the issues of marine optics include those by Barale (1991), Barale and Schlittenhardt (1993), Bukata *et al.* (1995), Gordon and Morel (1981, 1983), Gordon *et al.* (1975, 1985), Hooker *et al.* (1992), Jerlov (1976), Kirk (1981, 1984, 1994 a, b), Morel (1991), Morel and Prieur (1977) and Richardson (1996).

It rapidly becomes apparent in any study of the subject that there is no simple relation between, on the one hand, the concentration or the biological composition of an algal bloom and, on the other hand, the observed reflectance spectrum from the water in which the bloom occurs. The observed reflectance spectrum depends, for one thing, on the pigments present in the bloom.

There are three main groups of photosynthetic pigments: chlorophylls, carotenoids and phycobiliproteins (phycobilins). Common to all photosynthetic organisms that produce oxygen, chlorophyll-*a* is often used to calculate overall phytoplankton abundance, although it is highly variable depending on physiological condition, degree of light adaptation and state of degradation (Gieskes 1991, Stramski and Morel 1990, Wilhelm and Manns 1991). Chlorophyll-*a* has two absorbance peaks—at 433 nm (blue) and 686 nm (red)—and an overall reflectance spectrum similar to chlorophylls -*b*, -c_1, -c_2, -c_3, and -*d*.

Carotenoids, responsible for photoprotection, absorb high-energy short wavelength light below 500 nm. There are over 60 different types which all cover the same wavelength range, but the shape of each is unique. Some carotenoids (e.g. beta-carotene, zeaxanthin) can be found in many algal groups, but others are highly specific (e.g. myxoxanthophyll), and may thus be used to identify algal types.

Essentially, carotenoids absorb below 500 nm, phycobilins absorb between 550 nm and 650 nm, and chlorophylls absorb below 433 nm and above 690 nm (Richardson 1996). Selected pigment types and their significance are listed in table 4 (Richardson and Ambrosia 1997, p.80). However, much research, both on the shape of pigment absorption spectra (e.g. Hoepffner and Sathyendranath 1991, Sathyendranath *et al.* 1996) and the actual values of absorption coefficients (e.g. Bricaud *et al.* 1988) due to phytoplankton, is still required.

In addition to the pigment composition of an algal species, cell structure also contributes to overall reflectance characteristics. For instance, diatoms and coccolithophores, which consist largely of mineralized cell walls or scales, scatter light substantially more than naked flagellates; vacuole-bearing phytoplankton such as blue–green algae also scatter light much more intensely, as well as floating to the surface where they are more easily observed.

In addition to remotely sensed data in the visible range of the electromagnetic spectrum, there is also the possibility of the use of temperature, as determined from infrared scanner data, as an indicator of phytoplankton concentration. It has been shown that surficial cyanobacterial plumes in the southern Baltic Sea in July 1992 caused localized increases in sea surface temperature (SST) of up to 1.5°C (Kahru *et al.* 1993). This diurnal effect of increased absorption due to phytoplankton accumulation observed during low wind conditions could be used as an indicator of near-surface pigment concentration detectable by satellite.

High concentrations of phytoplankton permit relatively small amounts of solar energy to penetrate the water column, resulting in most of the energy being absorbed to heat the upper few metres. However, in the more oligotrophic, actively mixed, open ocean, as much as 40% of the visible energy incident on the surface penetrates to depths of more than 30 m (Lewis and Cullen 1991), making chlorophyll identification by heat-tracking more difficult.

Nitrite, a necessary phytoplankton nutrient, is generally supplied to the mixed layer from below the thermocline, allowing surface layer temperature to act as a tracer of nitrite concentration (Olaizola *et al.* 1995). The SST is easily determined through sensor thermal infrared channels, but this approach may only work in

Table 4. Significance of various pigments (Richardson and Anbrosia 1997).

Chlorophyll-*a*	Common to all algae; reveals overall concentration of phytoplankton
Chlorophyllide-*a*	Natural degradation product of chlorophyll-*a*; indicates overall health of sub-blooms
Chlorophyll-*b*	Specific to green algae (Chlorophytes)
Chlorophyll-c_1	Indicates presence of diatoms (subgroup of Chrysophytes)
Chlorophyll-c_2	Indicates presence of dinoflagellates (subgroup of Pyrrophytes)
Fucoxanthin	Indicates presence of diatoms (subgroup of Chrysophytes)
Diadinoxanthin	Indicates presence of dinoflagellates (subgroup of Phyrrophytes)
Myxoxanthophyll	Indicates distribution and abundance of cyanobacteria (myxoxanthophyll is a carotenoid only found in Cyanophytes—a cyanobacteria commonly called blue–green algae)

upwelling areas where a clear temperature signal can be related to an influx of deep, nutrient-rich water.

The collection and storage of field samples is an essential part of any study concerning a bloom event, with the collection of 'ground truth' samples taking a number of forms. This can be done, for example, with water bottle samples or with pump sampling. Water bottle samples should contain all but the rarest organisms in the water mass sampled and should include the whole size spectrum, from the largest entities like diatom colonies to the smallest single cells. Pump sampling involves much larger quantities of water and so allows the collection of the rarer species. This technique has its disadvantages, however, e.g. breaking up colonies, breaking off large *Chaetoceros setae*, and breaking into pieces of long pennate cells like *Thalassiothrix* spp. Water bottle and pump samples usually have to be concentrated to provide a sample large enough for species identification. It is also possible to sample using plankton nets. This is a more selective means of sampling with the mesh size and the speed of the boat all influencing the sample obtained. Net sampling does have the advantage that it provides a large enough quantity of a sample simultaneously for species identification. Other methods of obtaining samples in sufficiently large concentrations involve centrifuging, crude cultures and dilution cultures.

The Continuous Plankton Recorder (CPR) Programme monitors the near-surface plankton of the North Atlantic and North Sea on a monthly basis. A CPR is a device which is towed behind a ship at a depth of 10 m, with the ships used in the programme often being merchant ships or ships of opportunity. The device works through a continuous moving silk filter being wound through the instrument by a propeller. This silk can then be cut into sections, once returned to the laboratory, with each section representing ten nautical miles. Prior to being cut into strips a simple colour analysis of the filter is carried out to provide an indication of pigment concentration. Various laboratory procedures, including microscope analysis, are then undertaken to identify the plankton and zooplankton. The United Kingdom has run a CPR programme for approximately 60 years with the CPR database containing over 170 000 samples. Full details of the CPR programme can be found at the website of the Sir Alister Hardy Foundation for Ocean Sciences, located at

http://www.npm.ac.uk/sahfos.sahfos.html

The site also provides metadata from the CPR database, including the number of samples obtained per month and year for the user's geographical area of interest. A list of species identified can also be obtained.

The USA has maintained a CPR programme since the late 1960s, with merchant ships used as part of the Northeast Fisheries Science Center (NEFSC) programme that monitors changes in the US Northeast Shelf ecosystem. In addition to data being collected by the CPR instrument, expendable bathythermograph and surface temperature and salinity measurements are also routinely collected.

2.4. *Earth observation data. Atmospheric correction*

Let us suppose that we have used the appropriate calibration for data from a remote sensing system onboard a spacecraft or aircraft, and determined the intensity of the radiation reaching the remote sensing system. We then have to address the question of the determination of the water-leaving radiance. That is, we have to make corrections for the atmospheric influences that have affected the radiation during its passage from the surface of the water until it reached the instrument onboard the spacecraft. The principles of what is involved are not particularly difficult to establish. But it is extremely difficult to apply these principles in practice because:

- the atmospheric effects are very large;
- the atmosphere is a highly dynamic medium with properties that vary rapidly both spatially and temporally;
- there is not enough information about the actual state of the atmosphere at the time of the gathering of the data to enable the values of the necessary atmospheric parameters to be determined accurately.

The problem of making corrections for atmospheric effects is much more serious for optical and near-infrared wavelengths than it is for the thermal infrared wavelengths. The determination of SSTs from data obtained from the thermal infrared channels of the Advanced Very High Resolution Radiometer (AVHRR) is quite standard and atmospheric corrections can be performed quite successfully. Thus it is possible to determine the temperature of the surface of the sea to an accuracy of the order of 0.5 deg K in a temperature of about 300 K, i.e. with an error of less than 1%. When it comes to the visible bands, the atmospheric contribution to the signal received at the spacecraft may be as high as 50%, or even higher, of the received signal. In these circumstances it is clear that if one is to obtain any realistic estimate of the water-leaving radiance, a very good atmospheric correction procedure is required. A discussion of the principles involved in making corrections for atmospheric effects is given in chapter 8 of the book by Cracknell and Hayes (1991).

2.5. *Earth observation data. Pigment concentration algorithms*

We suppose that the necessary preliminaries of cloud detection, cloud elimination and geometrical rectification have all been performed on a remotely sensed ocean colour dataset. We also suppose that both the calibration procedures for the conversion of the output from the scanning system to determine the satellite-received radiance and the atmospheric correction have all been carried out on the dataset as well. This gives us the value of the water-leaving radiance. Then, of course, if one wants to extract pigment concentration one needs to have a very good algorithm that relates pigment concentration to water-leaving radiance. One can try to lump together the atmospheric correction procedure and the chlorophyll (or pigment) concentration calculation into a single procedure, but that obscures the fact that this covers two quite different physical processes.

Being realistic, if one has no simultaneous *in situ* pigment concentration data, one is doing quite well if one can determine the pigment concentration in the water to the nearest order of magnitude from the satellite data in the visible bands. If one does happen to have some simultaneous *in situ* pigment concentration data then one can use this to scale (or anchor) the satellite-retrieved values and obtain a more accurate map of pigment distribution. However, it is rather rare to have such simultaneous *in situ* data available.

Unlike the case of the determination of SSTs from thermal infrared remotely sensed data, there is no simple physical law or equation that can be inverted to determine the pigment concentrations in the near-surface ocean water. There are several reasons why there is no such simple algorithm for chlorophyll (or more general pigment) extraction. First, in some areas there are high concentrations of suspended sediments (total suspended matter) as well as of chlorophyll and there is no easy way of separating the contributions of the two materials to the reflectance of the water. Secondly, chlorophylls (and sediment) are not simple materials. A biological material may contain not just chlorophyll (-*a*, or -*b* etc.) but a number of other pigments as well. The concentration of chlorophyll is not unique to a given species of algae, but it will vary depending on the stage in the growth cycle, the exposure to light, etc. The reflectance, or spectral signature, can vary enormously, depending on the concentration, species, environmental conditions, and so on.

There are essentially three approaches by which measurements of spectral irradiance from waters can be used to estimate the concentrations of water quality parameters using remote sensing (Morel and Gordon 1980, Davis 1994).

(*a*) *Analytical approach.* In this approach the optical properties of the water column are physically related to the subsurface reflectance, and thence to the water-leaving radiance and thence, in turn, to the satellite-received radiance. The analytical approach involves inverting this approach to determine the values of the water quality parameters from the satellite-received signal.

(*b*) *Semi-analytical approach.* This approach uses spectra from characteristic regions of the image and knowledge of the spectral characteristics of the various water quality components to develop derivative or band ratio algorithms for those components. However, the coefficients from any such relationships are not likely to have any general validity and probably only apply to the data from which they were derived, with each new application requiring recalibration.

(*c*) *Empirical (statistical) approach.* This approach is based on the development of statistical relations between measured spectral values and measured water quality parameters. The limitations of this approach are that causal relationships between the parameters are not necessarily implied, and algorithms developed in this manner are frequently not generally applicable to other datasets. Nevertheless, empirical methods are by far the most common methods employed for algorithms for the coastal zone and they have been widely used in preparatory work for the Sea-Viewing Wide Field-of-View Sensor (SeaWiFS) system.

Some use has been made of neural networks for inversion modelling in an attempt to calculate chlorophyll, yellow substance and suspended sediment concentrations, plus atmospheric contributions from remotely sensed data, see e.g. Buckton *et al.* (1999), Keiner and Yan (1998), Pozdnyakov and Lyaskovky (1998) and Schiller and Doerffer (1999). In a procedure such as the use of neural networks, where no attention is paid to the physical processes involved, one might regard it as reasonable to try to lump together the atmospheric correction and the pigment algorithm stages and attempt to relate the calibrated satellite-received radiance directly to the pigment concentration in the water. However, even with neural networks the work that has been done so far has mostly concentrated on treating the two stages separately.

3. Satellites and sensors

The observation of algal blooms from space is based largely on visible band scanner data with some use of thermal infrared data as well. The first instrument to be flown specifically for ocean colour studies, the Coastal Zone Color Scanner (CZCS) which was flown on Nimbus-7, was launched in 1978. This has now been succeeded by numerous new generation satellite sensors with a greater number of channels, more accurate chlorophyll concentration algorithms, better atmospheric correction and improved signal to noise ratios (SNRs). What follows is a discussion on a number of past and current satellite sensors (not all of which were actually designed for ocean colour imaging) plus a look at the potential of some of the planned future missions.

3.1. *The CZCS (Coastal Zone Color Scanner)*

The CZCS was only ever operated on an intermittent schedule, due to power constraints and the operation of other instruments on the Nimbus-7 platform. Band 6 (the thermal infrared channel), failed in the first year of the mission. During 1981 it was established that the sensitivity of the other CZCS bands was degrading with time, in particular channel 4. In mid 1984 Nimbus-7 mission personnel experienced turn-on problems with the CZCS system which were related to power supply problems and the annual lower power summer season of Nimbus-7. Further to this, the CZCS started experiencing spontaneous shut downs which persisted for the rest of the mission. From 9 March 1986 to June 1986 the CZCS system was given the highest priority for the collection of a contemporaneous set of ocean colour data. It was turned off in June 1986 at the start of the low power season with the intention of turning it back on in December when power conditions would be more favourable. However, attempts to reactivate the CZCS system in December met with failure and the instrument was officially declared non-operational on 18 December 1986.

Data products derived from CZCS imagery include global maps of chlorophyll concentration, sediment distribution, gelbstoff concentration as a salinity indicator, and temperature maps of coastal waters and the open ocean. Further details concerning the CZCS and information concerning the availability of data can be obtained from

http://daac.gsfc.nasa.gov/CAMPAIGN_DOCS/OCDST/czcs_dataset.html

The Ocean Colour European Archive Network (OCEAN) project, which was set up in 1990, had the specific aims of generating a European ocean colour database from historical CZCS data covering the marine areas of interest to the European community. The OCEAN project was a joint initiative of the Joint Research Centre (JRC) of the European Commission (EC) and the European Space Agency (ESA). Approximately 18 000 CZCS level 1 images have been processed through the project, plus an additional 6000 level 2 and 3500 level 3 scenes. Full details of the OCEAN project can be found in the work of Barale *et al.* (1999), while Sturm *et al.* (1999) provide a complete description of the algorithms and calibration used in level 2 processing of the imagery.

Since ocean colour images from the CZCS instrument began to be released in 1978, hundreds of papers based on this dataset have been published. An excellent and comprehensive guide to the varied processing and analysis techniques stemming from work with CZCS imagery in the last decade, along with numerous case studies, is given by Barale and Schlittenhardt (1993).

3.2. *The AVHRR (Advanced Very High Resolution Radiometer)*

The AVHRR has a wide swath width, frequent coverage, and is an operational system with a long history of archived image data since 1979, which are comparatively inexpensive to acquire and process. AVHRR data therefore have the properties that are most important when creating a high-volume long-term database (Rud and Kahru 1994). The AVHRR was, of course, never intended as an instrument for ocean colour studies; it was originally designed and operated as a meteorological system which only subsequently happened to be found to be very suitable and appropriate for a whole range of non-meteorological studies (see Cracknell (1997) for details of many applications which benefit from the use of AVHRR data, as well as a thorough review of processing procedures and the system itself). Although the AVHRR onboard the National Oceanic and Atmospheric Administration (NOAA) series of satellites is less suitable spectrally for ocean colour research, it is still considered very useful due to its frequency of coverage, reliability, and long historical time series of archived data still continuing today. Whereas the experimental CZCS images tended to be processed long after they were generated, AVHRR data are increasingly being used in a near-real-time situation, which finally allows the academic theory of remote sensing to bring practical solutions to today's environmental problems.

3.3. *The ADEOS platform and its sensors*

The ADEOS platform, launched on 17 August 1996, carried a number of sensors designed for the monitoring of the Earth's oceans. However, contact was lost within the first twelve months of the mission, with the satellite officially out of operation by 30 June 1997. Three of the instruments flown on ADEOS will be covered here, namely the OCTS, AVNIR and POLDER sensors. A replacement satellite, ADEOS II, is currently being developed which will include a number of ocean monitoring instruments, including the GLI which will also be mentioned. A brief overview of the Japanese Earth Observation satellites and their instruments is provided by Tanaka (1998) and at various websites, some of which are included below. Some aspects of the ADEOS programme in relation to ocean colour are discussed by Kawamura *et al.* (1998), Kawata *et al.* (1998) and Toba (1998).

3.3.1. *OCTS (Ocean Colour and Temperature Scanner)*

The OCTS had a spatial resolution of 700 m with a swath of approximately 1400 km and a quantization of 10 bits. The sensor was able to tilt its line of sight by up to 20° from nadir to avoid sunglint, providing a temporal resolution of three days. Data were collected in eight visible and near-infrared and four thermal bands.

Further details concerning the OCTS instrument can be obtained from

http://hdsn.eoc.nasda.go.jp/guide/satellite/sendata/octs_e.html

while a complete discussion of the OCTS sensor, including instrument design, calibration, algorithms and products is provided by Kawamura *et al.* (1998). Brown (1997) gives an overview of OCTS-related activities at NOAA, including intended data products, which would have been freely available to the user community for non-commercial purposes. Fukushima *et al.* (1998) provide a complete description of the atmospheric correction algorithms applied to OCTS data. The aerosol models used for OCTS atmospheric correction are essentially the same as those proposed by Gordon and Wang (1994) for the SeaWiFS sensor; however an Asian dust model has also been added to take into account the unique feature of local aerosols over East Asian waters. This provides ten aerosol models in total, covering tropospheric, coastal and maritime aerosol distributions.

Some examples of work involving OCTS data being used to map chlorophyll concentration are given by Inagake and Saitoh (1998), Kishino *et al.* (1998), Murakami (1998), Saitoh *et al.* (1998) and Yokouchi *et al.* (1998).

3.3.2. *The AVNIR (Advanced Visible and Near-Infrared Radiometer)*

The AVNIR was an electronic scanning radiometer with four spectral bands in the visible and near-infrared at 16 m spatial resolution and one panchromatic band at 8 m resolution. The swath width is 80 km with the ability to tilt up to 40° off nadir.

Information concerning this instrument can be found at the website

http://www.eoc.nasda.go.jp/guide/satellite/sendata/avnir_e.html

3.3.3. *The POLDER (Polarization and Directionality of the Earth's Reflectances)*

The POLDER was a multi-band imaging radiometer/polarimeter designed to observe the polarization, directional and spectral characteristics of solar light reflected from aerosols, clouds, oceans and land surfaces. Further information concerning the POLDER instrument can be obtained from

http://www.eoc.nasda.go.jp/guide/satellite/sendata/polder_e.html

POLDER II is planned to be deployed on the ADEOS II satellite.

3.3.4. *The GLI (Global Imager)*

Of OCTS heritage, the GLI instrument is due to be flown on the ADEOS II satellite. The GLI has 34 bands in total (22 in the visible and near-infrared, five in the short-wavelength infrared region and seven in the middle and thermal infrared). The swath width will be 1600 km with a 1 km spatial resolution at nadir, however some of the bands in the visible and near-infrared and the shortwave length regions will have a resolution of 250 m at nadir. For further information, visit the website

http://www.eoc.nasda.go.jp/guide/satellite/sendata/gli_e.html

Kahru and Mitchell (1998) highlighted the potential of the GLI for distinguishing red tides from other algal blooms due to significant differentiation when reflectances in the ultraviolet part of the spectrum were evaluated relative to chlorophyll-*a*. The next generation of GLI instruments is already in the planning stage, with measurement in a continuous spectrum a candidate aim of the ADEOS III mission (Kramer 1996).

3.4. *MOS (Multispectral Optoelectronic Scanner)*

MOS is an advanced imaging spectrometer for the VNIR and SWIR spectrum of 400–1600 nm. The apparatus consists of three complementary instruments, together used to observe ocean colour, phytoplankton, surface–atmosphere interaction, man-made aerosols, cloudiness characteristics, and other parameters (Kramer 1996). MOS-A, providing estimates of aerosol optical thickness, is essentially used for atmospheric correction of the multispectral data contained in MOS-B.

Ground stations for the downloading of MOS data from the IRS-P3 platform are located in Hyderabad (India) and Neustrelitz (Germany), which cover the Indian subcontinent, the Arabian Sea, and the entire European land and coastal regions. Additional stations for wider coverage are currently under discussion (Zimmerman and Neumann 1997).

3.5. *SeaWiFS (Sea-Viewing Wide Field-of-view Sensor)*

SeaWiFS was launched in 1997 aboard the Orbview-2 platform as a successor to the CZCS instrument. The sensor has a 45° swath and a spatial resolution of either 1.1 km LAC (Local Area Coverage) or 4 km GAC (Global Area Coverage) with a repeat period of one day. The instrument's eight spectral bands are indicated in table 5.

The instrument is able to tilt up to 20° from nadir to avoid sunglint from the sea surface. Ground processing is simplified due to the entire scanner being tilted, thus ensuring that the SeaWiFS calibration, polarization and angular scanning characteristics will be identical for all tilt positions. Improvements over the CZCS include more bands, a higher SNR, improved atmospheric correction capabilities from two near-infrared bands, and the construction of more reliable bio-optical algorithms to derive plant biomass, chlorophyll-*a* concentration (for carbon fixation) and water clarity. Originally designed to image only open ocean regions, the SeaWiFS gain calibration has evolved from linear to bi-linear to include land and coastal areas without sensor saturation (Hill and Pastrone 1997). The SeaWiFS homepage containing further information concerning the instrument, technical reports and datasets can be found at

http://seawifs.gsfc.nasa.gov/SEAWIFS.html

A detailed discussion of ocean colour algorithms for the SeaWiFS instrument can be found in the work of O'Reilly *et al.* (1998). A summary of the services of the Goddard Distributed Active Archive Center (DAAC) can be found in the work of Acker *et al.* (1998).

3.6. *MERIS (Medium Resolution Imaging Spectrometer)*

MERIS is to be launched as part of the payload aboard ENVISAT-1 in 2000, with an expected lifetime of five years. The instrument is a fifteen channel, programmable pushbroom spectrometer that is able to change the location, width and gain of its bands, depending on the mission requirements. Since MERIS is a multipurpose sensor, designed to look at land, ocean and atmospheric parameters, the instrument has been designed to encompass a large dynamic range to cope with signals received from bright targets (such as clouds) to weaker targets (such as ocean colour). The work of Rast *et al.* (1999) provides a complete description of the MERIS instrument with further details concerning MERIS and ENVISAT being available from

http://envisat.estec.esa.nl/

Table 5. The SeaWiFS spectral bands.

Band number	Centre wavelength (nm)	Bandwidth (nm)
1	412	20
2	443	20
3	490	20
4	510	20
5	555	20
6	670	20
7	765	40
8	865	40

Details concerning the MERIS ground segment, including product description can be found in the work of Merheim-Kealy *et al.* (1999).

3.7. *MODIS (Moderate Resolution Imaging Spectroradiometer)*

The EOS programme is a NASA (National Aeronautics and Space Administration) initiative, and is the principal element within the Mission To Planet Earth of the US Global Change Research Program (GCRP). Each satellite will carry several sensors, but the MODIS instrument will be the prime sensor on the a.m. and p.m. series. The objective will be to measure biological and physical processes on a global basis, on timescales of one to two days. The first spacecraft in this series, the EOS-AM platform, was successfully launched in December 1999.

Using thirty six discrete bands in the range 0.4–14.5 μm, MODIS is designed for the observation of ocean colour, phytoplankton biochemistry, land and cloud properties, atmospheric constituents, and temperature, with GAC provided every two days. Some standard data products for oceanographic purposes include ocean colour, chlorophyll-*a* concentration from 0.05 to 50 $mg\,m^{-3}$ for Case 1 waters, and chlorophyll fluorescence at the sea surface (Kramer 1996).

MODIS will be the first satellite instrument designed to measure chlorophyll fluorescence which accounts for approximately 3% of the light energy absorbed by phytoplankton and appears as a distinct peak at 683 nm (Esaias *et al.* 1998). Using three narrow bands centred at 665.1, 676.7 and 746.3 nm MODIS should be able to detect fluorescence signals at 676.7 nm (fluorescence line height) as low as $0.012\,W\,m^{-2}\,sr^{-1}\,mm^{-1}$.

3.8. *OCI (Ocean Colour Imager)*

The OCI was launched aboard ROCSAT-1, Taiwan's first scientific experimental satellite during early 1999. The sensor has seven spectral bands, of which six are centred at identical positions to those on SeaWiFS (443 nm, 490 nm, 510 nm, 555 nm, 670 nm and 865 nm). The seventh band is a repeat of band four (555 nm) with all bands having a width of 20 nm. ROCSAT-1 has an orbital inclination of 35° providing an opportunity to monitor low latitude oceans from 9:00 to 15:00 local time, but at the expense of monitoring the higher latitudes. Further constraints include the need for maximum contact time with the ground station in Taiwan; thus the temporal resolution is 52 days. The ROCSAT homepage can be found at

http://www.oci.ntou.edu.tw/

with OCI data available free to educational and scientific communities.

3.9. *Landsat TM (Thematic Mapper) and MSS (Multi Spectral Scanner)*

The Landsat satellite programme has been operating since July 1972, with each of the first five satellites in the series carrying the MSS. This sensor collects data in four bands in the visible and near-infrared regions with a spatial resolution of either 79 m or 82 m (depending on the satellite in the series). The TM instrument was only carried on Landsat-4 and Landsat-5 and represented a considerable improvement both in spectral and spatial resolution over the MSS. Data were collected in seven spectral bands through the visible, near-infrared and thermal infrared wavelength ranges. Landsat-7, which carries an Enhanced Thematic Mapper (ETM+) with a panchromatic spectral band with a ground resolution of 13 m × 15 m has recently been launched successfully. Further information concerning the Landsat series of satellites can be obtained from most remote sensing textbooks (see e.g. Drury 1990, Lillesand and Kiefer 1994, Sabins 1997).

Although never designed for studies of oceans, Landsat has nevertheless been used in some studies of algal blooms; it has a very long revisit time and so only very occasional images of an algal bloom can be obtained.

3.10. *Combined satellite approach*

The remote sensing of the Earth's oceans can be hindered due to both cloud cover and sunglint, thereby effectively reducing the temporal resolution of a single satellite system. Combining data from different satellite systems allows better monitoring of algal blooms. Gade *et al.* (1998) used data from AVHRR, Landsat TM and ERS SAR to monitor algal blooms in the Baltic. Gregg and Woodward (1998) examined the potential of combining MODIS and SeaWiFS data, with results suggesting a 40–47% increase in global coverage over using SeaWiFS alone in one day.

The SIMBIOS project has been developing methods for the comparison and possible merging of data products from various ocean colour satellite systems. This includes the German MOS, the Japanese OCTS and GLI, the European MERIS and the French POLDER-1 and -2 instruments (McClain and Fargion 1999, Wang *et al.* 1999).

3.11. *Airborne sensors*

Although airborne sensors do not provide the continuous temporal resolution or global coverage of a satellite system, they do offer a number of advantages. Often more spectral channels are available on an airborne sensor as they are not limited by data transmission rates, while the spatial resolution is higher, partially due to the lower altitudes from which data are obtained. This has particular advantages in the coastal zone where the coarse pixels of some satellite sensors contain the signal from both the land and water. Moreover, an aircraft can be flown repeatedly over a bloom at intervals that are specified by the observer rather than being determined by the orbital geometry for a spacecraft and any tilting mechanism in the space-borne instrument. Moreover, if one has an appropriate instrument and ready access to a suitable aircraft, then a set of flights can be mounted at very short notice when it becomes apparent that an algal bloom is occurring in a particular area. A number of authors have used airborne sensors for the study of algal blooms; for some information on the instruments flown see, for instance, the work of Kramer (1996).

4. Bloom monitoring

Operational real-time monitoring of the location, extent, movement and growth rate of a phytoplankton bloom is an important challenge at present. Theoretical modelling of the likely evolution and movement of blooms is a very important area of investigation, but such work is still in the research phase, with collaborations between government organizations and research labs ongoing (CEO 1995). Critically, archived Earth observation data are being used in hindsight to assess the prevailing conditions during bloom formation, in order to pinpoint parameters for future bloom forecasting. Monitoring essentially acts as the precursor to bloom prediction, which is perhaps of more practical use but which is presently not feasible.

Under EC Directive 91/492, governments of European Union member states are obliged to monitor algal blooms in coastal waters, due to the possible threat to public health posed by toxic algae in shellfish production areas. In order to extend knowledge of the temporal and spatial distribution and thus the scale of the problem of such blooms, remotely sensed imagery is invaluable as a source of frequent, synoptical information. Real-time extraction of this information is vital if it is to be put to practical use in monitoring procedures.

Some operational systems currently in use are now summarized.

4.1. *United Kingdom*

In the UK, the National Rivers Authority (NRA) for England and Wales and the Ministry for Agriculture, Fisheries and Food (MAFF) routinely gather information on algal blooms, with local authorities monitoring the situation from harbour walls every two (May to October) to four weeks (November to April). Monthly sampling of shellfish toxin levels are also measured at nineteen sites around the coast (CEO 1995).

Synoptic information about the occurrence of algae in the UK's coastal waters is desperately needed to supplement the point-sampling techniques already used, which often leave blooms undetected. The NRA occasionally (every three months) supplements *in situ* measurements of coastal waters with Compact Airborne Spectral Imager (CASI) data, but the temporal and spatial resolutions of these data fall far short of the requirements of a comprehensive monitoring programme.

An operational system capable of the detection and monitoring of algal blooms and forecasting their growth and movement using Earth observation data is currently being developed in the UK by Anderson *et al.* (1997). The first phase of this project—a feasibility study involving the development of algorithms and models for the detection and classification of blooms—is still being completed, with the combination of *in situ* data and imagery from an airborne imaging spectrometer.

4.2. *Brittany (France: IFREMER)*

The Brittany Nearshore Information System catalogues natural and anthropogenic proliferation factors causing coastal eutrophication, and maps observed and potential eutrophication-sensitive zones using spatial and statistical analysis tools (Urvois *et al.* 1994). A digital atlas has been compiled (with modest AVHRR input) and stored in a geographic information system (GIS) to allow rapid evaluation of hypotheses and appropriate spatial extrapolation. This information system was applied to the problem of ulva proliferation with successful results. Certain sites were designated as potentially vulnerable to green tides if triggered by a slight increase in nutrient input at higher temperatures, and long residence time (over two days) was highlighted by advanced factor analysis as the most important marine parameter. This evaluation study will soon be extended to phytoplankton blooms, with the index of coastal vulnerability to eutrophication a potentially useful tool in bloom prediction.

4.3. *Norway*

The Norwegian operational ocean monitoring and forecasting system (HOV) collates data using models that incorporate parameters relating to marine meteorology, physical oceanography, water quality and biological processes such as algal blooms. The aim is to provide a service which monitors ongoing processes, forecasts up to ten days in advance, and also evaluates climatological trends on a scale of months to a century (Sloggett 1994, Victorov 1996).

Another system, the MARine COASTal information system (MARCOAST), is run by the Nansen Environmental and Remote Sensing Centre (NERSC), affiliated with the University of Bergen. This system facilitates the integrated use of remotely sensed data, *in situ* data and numerical models to allow monitoring and mapping of occurrences such as marine pollution, mesoscale coastal circulation, marine wind fields, natural surfactants and algal blooms.

4.4. *Sweden*

The main application areas for the Swedish marine routine based at the Swedish Meteorological and Hydrological Institute (SMHI) include the monitoring of SST and blue–green algae in the Baltic Sea, using NOAA/AVHRR and Meteosat data (Victorov 1996).

Rud and Kahru (1994) made use of a system based in Stockholm University, in which AVHRR images of the Baltic Proper were processed and interpreted twice a day for a month, accumulated into maps, and distributed to both the 'Information Centre for the Baltic Proper' at the county administration in Stockholm, and the Finnish Institute of Marine Research in Helsinki. Near-real-time information of the location and spatial extent of a bloom could then be transferred to the relevant local authorities for appropriate action.

4.5. *The Netherlands (Rijkswaterstaat)*

A Netherlands framework programme on remote sensing and water quality has been established, called REWANET, the aim of which is to create operational applications of remote sensing for water quality management and policy decision making in the Netherlands (Allewijn *et al.* 1995). Coordination of research on operational monitoring networks and integration of information from EO data, numerical modelling and GIS analysis are two of the primary objectives of REWANET.

Using automatically processed NOAA/AVHRR satellite imagery, weekly and monthly composite images are compiled and quantitative products created using *in situ* data. Satellite-image-based informational products are presented for the North Sea area between 50° and 60° N and for the Ijsselmeer. Routinely issued output products include red reflectance maps based on AVHRR channels 1 and 2, subsequently calculated total suspended matter concentrations (at only 50% accuracy however), SST charts using channels 4 and 5 (with ± 0.5°C accuracy) and Normalized Difference Vegetation Index (NDVI) maps, which are used to monitor floating algae in freshwater bodies (Victorov 1996). This information is distributed within one day of the NOAA overpass, and can thus be considered to be a near-real-time monitoring system.

4.6. *The North Sea*

A pilot project to investigate the potential use of remotely sensed data in the development, calibration and validation of water quality and ecological models for the North Sea is being undertaken (RESTWAQ: REmote Sensing as a Tool for improved knowledge on WAter Quality and ecology in large water bodies) in two phases (Allewijn *et al.* 1995). Phase 1 will develop a new generation of well calibrated models, which will then be used in an applied context in phase 2; the resulting tools and procedures can also be extended to use in other large water bodies around the world.

4.7. *Italy*

Ippoliti *et al.* (1997) present the results of the application of remote sensing techniques and GIS analysis to surveillance of a protected coastal humid zone in Torre Guaceto, Italy. Landsat TM data were used to monitor vegetation stress as well as water quality parameters such as chlorophyll and transparency level, and outputs in the form of thematic maps and statistical information were shown to be used in the operational management tasks concerning this area.

4.8. *USA*

Established in 1988, NOAA's Coastwatch programme delivers satellite information products and *in situ* data to federal, state and local marine scientists and coastal resource managers in a quality controlled, near-real-time operational system. SST, turbidity and ocean chlorophyll of the coastal and Great Lakes regions of the USA are some of the parameters extracted for public data products, and these will be improved with future data from the SeaWiFS sensor system (Victorov 1996). Further details concerning this programme can be found at

http://www.nodc.noaa.gov/NCAAS/ncaas-home.html

4.9. *Joint European level organizations*

At the European level, the *ad hoc* Working Group on Eutrophication (EUT) of the Oslo–Paris Commission (OSPARCOM) receives data on algal blooms from individual countries, but at present there is no European-wide coordination of monitoring activities in and around the North Sea (CEO 1995).

Set up in 1990 by the Institute for Remote Sensing Applications (IRSA) of the EC JRC and ESA, the OCEAN (Ocean Color European Archive Network) project was intended to take advantage of existing CZCS data and prepare for the exploitation of future ocean colour space missions (Barale and Schlittenhardt 1994 b). A European historical database for the environment was built, and scientific tools needed for data manipulation were developed. The project succeeded in focusing into a network the studies of several European research groups, and valuable exploration of a number of marginal and enclosed basins and coastal regions was undertaken. Value-added products relating to the major European seas were thus created. Continuing the progress of OCEAN, the Commission of the European Communities (CEC) and ESA established the Ocean Colour Techniques for Observation, Processing and Utilization Systems (OCTOPUS) project (Barale and Schlittenhardt 1994a, Sloggett 1994, Sloggett *et al.* 1995).

In order to facilitate access to EO data from disparate sources, the JRC in Ispra established a European-Wide Service Exchange (EWSE) and a single-interface web-based access which allows simultaneous geo-temporal searching of previously disjointed data sites. This has now been changed to INFEO (INFormation on Earth Observation) which offers access to Earth observation information and services and to data catalogues around the world:

http://infeo.ceo.org

4.10. *Global Ocean Observing System (GOOS)*

The Global Ocean Observing System (GOOS) is a coordinated international system, created in 1991, to improve the management of seas and oceans and to improve climate forecasts. Part of an Integrated Global Observation Strategy (IGOS) involving UN agencies working with satellite organizations, GOOS forms the ocean component of the Global Climate Observing System and the marine/coastal component of the Global Terrestrial Observing System. Further details concerning the GOOS programme can be found at

http://ioc.unesco.org/goos/

The Scientific Committee on Oceanic Research (SCOR) was established in 1957 as a non-governmental organization for the promotion and coordination of international oceanographic activities. SCOR has 39 member countries from across the globe. However, it does not run large research programmes, focusing rather on working groups, of which there are currently fifteen, and steering committees.

One of the current steering activities of the SCOR programme is the Global Ecology and Oceanography of Harmful Algal Blooms (GEOHAB) group which is trying to further scientific advancement in the understanding of HABs through the coordination of scientific research across international and multi-disciplinary boundaries. GEOHAB also identifies targeted studies on organisms, processes, methods and observation technologies that are needed to support interdisciplinary research. It is hoped that links between GEOHAB and GOOS will lead to global observation systems helping to resolve influences of environmental factors and trends in harmful algal bloom occurrence. An improved understanding of the physical and chemical forcing of ecosystems plus human influence will be used to improve strategies for the monitoring and prediction of HABs. Further details of the GEOHAB programme can be found at

http://ioc.unesco.org/hab/GEOHAB.htm

The Intergovernmental Oceanographic Commission (IOC) was founded in 1960. It is part of UNESCO and its role has focused on promoting marine science investigations and related ocean services. The main subsidiary body within the IOC that is concerned with HABs is the Ocean Science in Relation to Living Resources (OSLR) group. This body has a number of roles including the establishment of the GEOHAB programme with the SCOR, the Working Group on Harmful Algal Bloom Dynamics (WGHABD) as a Study Group researching the dynamics of algal blooms. The main aim of this working group was to outline the various physical, chemical and biological interactions associated with HABs and to define the main gaps in research. The IOC has also formed the IOC Science and Communication Centre on Harmful Algae (IOC SCC CPH), whose activities include: (1) direct assistance to developing countries where problems with toxic algal blooms occur; (2) training and capacity building; and (3) research activities in relevant fields of toxic algae. A second science and communication centre on harmful algae has also been set up with the IEO (Instituto Español de Oceanografia) in Vigo, Spain.

Details concerning the IOC can be found at

http://ioc.unesco.org/iocweb/default.htm

while details concerning the HAB programme are located at

http://ioc.unesco.org/hab/default.htm

The Land–Ocean Interactions in the Coastal Zone (LOICZ) programme is part of the International Geosphere–Biosphere Programme (IGBP). LOICZ focuses on the geographical areas where land, ocean and atmosphere all interact. Established in 1993, the project was set to run for a total of ten years with the overall goal of determining at regional and global scales how changes in various components of the Earth system are affecting coastal zones and altering their role in global cycles. Further details can be found at

http://www.nioz.nl/loicz/info.htm

4.11. *Resources*

There are numerous databases and information sites on the internet concerning toxic algal blooms and related subjects. It would be impossible to list them all here so a brief selection is listed here to provide an indication of the resources available.

There are several databases that provide information concerning scientists and institutions that carry out research in marine and freshwater environments. The IOC has one such database, the Global Directory of Marine (and Freshwater) Professionals (GLODIR). With over 6000 entries, it contains information on individual scientists and their scientific interests. Information from the database is free (it can only be used for non-profit purposes). Scientists are also able to add new records and edit existing ones via the internet.

The IOC has the Harmful Algae Bloom Expert Directory (HABDIR). This is a searchable version of the second edition of the directory that was published in 1995 as '*International Directory of Experts in Toxic and Harmful Microalgae and their effects on Fisheries and Public Health*' by Dr Alan White and Woods Hole Oceanographic Institution Sea Grant Program. The online version was prepared by the IOC Science and Communication Centre on Harmful Algae at the University of Copenhagen.

The Marine Environmental Data Information Referral Catalogue (MEDI) is a directory system for datasets, data catalogues and data inventories within the framework of the IOC and is in the process of developing their successful hard-copy catalogue into an online database so that it can be searched conveniently and kept up-to-date.

The European Directory of Marine Environmental Data (EDMED)

(http://www.nbi.ac.uk/bodc/edmed.html)

provides a computer searchable directory of datasets relating to the marine environment compiled in collaboration with centres in eleven European countries. EDMED was developed and coordinated by the British Oceanographic Data Centre (BODC) and was funded by the Marine Science and Technology Programme (MAST) of the European Commission. Datasets can be searched for using one or more EDMED search tables. All tables (except Area Type) allow multiple selections to be made. Alternatively, one can search for data holding centres by country.

Similarities in the data structures already exist between some of these databases, allowing a direct mapping between fields (such as EDMED and MEDI), but standard metadata descriptors are not yet implemented across all these databases. Both the CEO and the IOC have identified the high priority of using metadata standards and are currently developing such standards (but for their own specialized fields).

The Alg@line database provides extensive information concerning algal blooms in the Baltic Sea. Data sources include satellite imagery, buoy recordings and automated sampling onboard ships of opportunity. The project is run by a number of research institutes (Finnish Institute of Marine Research, Estonian Marine Institute, Uusimaa Regional Environment Center, City of Helsinki Environment

Center, Southeast Finland Regional Environment Centre and the Finnish Environment Institute, links to all these sites are included in the Alg@line pages), with the Silja Line and Transfennica shipping companies cooperating with the project. The database contains measurements including harmful substances, nutrients, oxygen, plankton and flow. It is possible to search the database either through a measurement parameter on a pre-defined geographical location within the Baltic Sea or through a text search. Information is made available to users in the form of reports dated as when the relevant activity occurred. Information contained within the reports includes maps of the extent and coverage of any algal blooms, plus charts of chlorophyll concentration along ferry routes. The database can be found at

http://meri.fimr.fi/algaline/zpl1.nsf

Details concerning the CPR programme started in the Baltic are also available from the Alg@line website. The CPR database held by the Sir Alister Hardy Foundation for Ocean Sciences, is located at

http://www.npm.ac.uk/sahfos/sahfos.html

The National University of Ireland, Galway, has a 'Seaweed' site on the internet, providing an array of information concerning algae and where to obtain information on it. The site contains several databases including literature, people and seaweed databases. The literature database allows users to carry out an author, year or keyword search (of the title) of various periodicals in the field. The people database lets users search for scientists, etc. with various search criteria. The 'seaweed' database provides information on the scientific names of seaweed. Further to the three databases, additional information from this site includes details of various culture collections from both within and outside Europe. The 'Seaweed' site is located at

http://seaweed.ucg.ie/Seaweed.html

The University of Texas maintains an extensive culture collection of over 2100 items. Details concerning media recipes and online ordering can be found at

http://www.bio.utexas.edu/research/utex/

The 'Culture Collection of Algae and Protozoa' (CCAP) is located at the Dunstaffnage Marine Laboratory, Oban, and the Institute of Freshwater Ecology Windermere Laboratory, Ambleside (both in the UK). The collection contains approximately 2000 strains of algae and protozoa maintained across the two laboratories. Details of the project (both sites and information on ordering) can be obtained from

http://www.ife.ac.uk/ccap/

The University of Toronto, Canada also has a culture collection, with a list of cultures and ordering information located at

http://www.botany.utoronto.ca/utcc/index.stm

Another Canadian culture collection is the North East Pacific Culture Collection (NEPCC), located in British Columbia. Further information can be found at

http://www.ocgy.ubc.ca/projects/nepcc/backgrnd.htm

Another culture collection whose details are available online is the Provasoli–Guillard National Center for Culture of Marine Phytoplankton (CCMP), USA, which holds approximately 1450 strains of which the majority are marine phytoplankton. The website for further details is

http://ccmp.bigelow.org/

The Tjarno Marine Biological Laboratory of the Gotenborg University and Stockholm University provides numerous downloads from its website linked with algal research. The North East Atlantic Taxa pages provide downloadable acrobat files containing lists of marine organisms contained within a defined geographical area. Another database from the same organization provides the Biographical Etymology of Marine Organism Names (BEMON). This is essentially a collection of short biographies of taxonomists working in the marine environment. Full details of both of these databases can be found at

http://www.tmbl.gu.se/

The University Marine Biological Station Millport, located on the Isle of Cumbrae, Scotland, although essentially a teaching and research facility at both undergraduate and postgraduate levels, is also the largest supplier of marine plant and animal specimens in the UK. Living or preserved specimens can be supplied either nationally or internationally with further details available from the website, located at

http://www.gla.ac.uk/Acad/Marine/

Satellite data are available from a number of organizations and sites covering a number of satellite sensors. The OCEAN project, mentioned in §3.1, contains an archive of over 18 000 CZCS images from over Europe. Further to this, the project has been expanded to include Ocean Colour Techniques for Observation, Processing and Utilisation Systems (OCTOPUS) with the aim of exploiting data from new generation ocean colour sensors. SeaWiFS data of European waters in various formats are available through this project. A further project operated through this organization is the Cloud and Ocean Remote Sensing around Africa (CORSA), which includes weekly SST maps and cloud classification products from around Africa. Details of all of these projects can be found from the Space Applications Institute (SAI) of the European Commission Joint Research Centre

http://me-www.jrc.it/

NASA's Physical Oceanography and Distributed Active Archive Centre (PODACC) contains an extensive archive from a host of satellites and sensors, including the CZCS, AVHRR, SSM/I and NSCAT. Oceanographic parameter products include atmospheric moisture, SST, tide models and multi-parameter data collections. Data can be ordered via the main website at

http://podaac-www.jpl.nasa.gov/

The Geography Department of the University of Stockholm maintains an online algal bloom browser of AVHRR images of the Baltic Sea. The browser contains an archive of images dating back to 1996, but is also updated on a daily basis with new images. Details concerning bloom events are also available with blooms outlined on satellite images. The browser can be found at

http://wwwmarin.natgeo.su.se/~ab/

4.12. *Models*

There have been attempts to create models of algal dynamics using information concerning nutrient availability, hours of sunshine and temperature indicator (see, for instance, Franks 1997, Geider and Platt 1986, Geider *et al.* 1996, 1998).

5. The ABDMAP workshops

5.1. *Workshop 1, ABDMAP Overview*

The introductory ABDMAP workshop was held in Dundee in May 1997. This opening workshop of the ABDMAP project included presentations by a number of speakers from the team members plus other guest speakers with expertise in the application of remote sensing technologies for algal bloom detection, monitoring and prediction. The programme was designed to give participants of the workshop an overview of the ABDMAP Concerted Action and the CEO programme itself, before presenting various examples of the role of remotely sensed data in algal bloom detection, monitoring and prediction. In addition to the ABDMAP team members, 22 end users and researchers (mostly from the UK) attended the workshop. Participants were present from a harbour authority (Orkney Islands Council), the Scottish Environment Protection Agency, the Scottish Office Agriculture, Environment & Fisheries Department, a regional Environment Agency office and a central Environment Agency office. In addition, a number of members of the academic community were present. The main points emerging from the discussion included the following.

There are a broad range of potential end users, and their needs are likely to be different. The need for data presented as visual products was identified, along with the need for an educating process. The uncertainty over the interpretation of data was identified as a problem.

On the question of cost effectiveness, the following conclusions were drawn.

- Cost effectiveness is difficult to assess as it depends upon the scope being considered.
- Image costs are perceived as a major limitation.
- End users have got to work within the context of diminishing resources.
- A full impact assessment is required.
- Cost effectiveness will also depend upon the definition of the economic worth of different areas.
- The overall conclusion was that Earth observation data is the only option to give spatial coverage.

The geographical importance of the concern about algal blooms was considered. There is an apparent increase in the problem of algal blooms, but this needs proof. The current impression of the scale of the problem was that there are localized problems in the Mediterranean Sea and diffuse problems in the North Sea, but it was noted that at present the current information is limited and inconclusive. One proposed solution was the development and evaluation of a long-term archive of algal bloom related data (including *in situ* and Earth observation data).

Detection of algal blooms was considered possible if the blooms meet certain criteria, namely:

- detection is carried out in cloud-free conditions;
- the bloom is at or very near to the surface;
- the bloom causes noticeable change in SST or ocean colour;
- turbidity, which may affect the signal, is considered.

It was noted that algal bloom management issues tend to affect coastal zones, and that although EO data may detect oceanic blooms, which are of academic interest, management is more important in the coastal zone. However, airborne sensors may complement satellite observations.

The identification of bloom species from remotely sensed data was considered unlikely given the great diversity and very minor morphological differences, but it may be possible to detect some classes of algae (e.g. coccolithophores) or red tides by this technique.

The prediction of algal blooms was considered to be potentially achievable if it is possible to link particular meteorological/SST/ocean colour data with conditions preceding and during blooms. It was noted that this would require long-term data analysis of trends and ground truthing.

5.2. *Workshop 2, Algal bloom monitoring, anthropogenic and natural causes*

The second ABDMAP workshop was held in Kiel in September 1997. This workshop focused on the problem of monitoring algal blooms using remote sensing, and the relative importance of natural or anthropogenic influences on the formation of blooms. The workshop was attended by about 35 participants, including ABDMAP team members, along with a good cross section from academic and research institutions and end user organizations.

Rather than break into working groups as in the introductory workshop, this workshop focused on gaining an overview of different algal bloom monitoring programmes from the end users present at the workshop. These included representatives from the Danish National Environmental Research Institute of the Danish Ministry of Environment and Energy, the Schleswig-Holstein Environment Protection Agency, the Lower Saxony Agency for Ecology and a marine research and broadcast agency among others. It was recognized that a range of monitoring programmes currently exist, depending upon the interpretation of European directives and legislation, the organization responsible and the region or state responsible, and the past history of algal blooms in any particular location. The majority of participants recognized the role of EO data in a detection and monitoring programme, but only when it is well integrated with other data sources. Concern was also expressed about the cost implications of EO data, the repeat cycle and continuity of data, along with questions over the level of confidence in the information generated from EO data.

It was recognized that EO data have some limitations for algal bloom monitoring and detection; these include the question of scale (especially for coastal blooms) and the detection level from EO data, as well as the familiar problems of cloud cover and the cost of data. It was also noted that *in situ* monitoring techniques are equally imperfect. The implementation of an integrated detection and monitoring system was suggested, comprising various components:

- discrete sampling;
- Earth observation data (satellite);
- airborne remote sensing (multi-spectral and fluorescence measurements);
- hydrographical modelling;
- database of known species, species succession for specific regions.

5.3. *Workshop 3, Public Health*

A two-day meeting was hosted by the Laboratorio di Igiene Ambientale, at the Istituto Superiore di Sanita, Rome, Italy. End user attendance was high, so their contributions provided useful input and valuable insight into the current monitoring programmes, the scale of the problem and identified socio-economic impacts. This workshop focused on the problem of the Mediterranean basin and in particular on harmful algae. It was organized with morning sessions of formal presentations, followed by afternoon sessions structured into small discussion groups on the first day, and one large discussion group on the second. Both sessions involved end users, who were encouraged to participate fully, through introducing their activities, problems, and posing any questions. Through the discussion sessions, it was considered how remote-sensing techniques could be utilized by end users for their research or monitoring activities. ABDMAP team members, speakers and 45 other participants (largely drawn from the end user and public health communities within the Mediterranean region) attended the workshop.

The participants were split into four working groups and several topics for discussion were put to each of the working groups. The outcome of the discussion is now summarized for each discussion topic in turn.

- *What parameters affect the occurrence of* toxic *species? Can these parameters be studied by remote sensing?*

A clear distinction was made between the physical and biological factors affecting the occurrence of a bloom. Temperature was identified as a key parameter, along with the condition of the water column. It was noted that, in the Mediterranean, HABs were closely related to and restricted to coastal waters, and quite often at depths of less than 6–10 m. The typical extent of a HAB in the Mediterranean was noted as from 100 m up to 1–4 km. In addition, non-toxic red tides extending to 100–150 km in length were a frequent phenomenon occurring every two or three years. There is clearly a role for remotely sensed data in providing SST, and also for the identification of upwelling areas, and river plumes and runoff from rivers. It was noted that these parameters would be more useful if integrated into a hydrodynamic model. There was also some consideration of the role of accessory pigments to indicate the likelihood of a bloom being toxic.

- *Are toxic algal blooms increasing in number or is it just that there is an increase in reporting that is occurring?*

A definitive answer to such a question would require a long-term monitoring programme, which has not existed to date. However, it was noted that there is currently more monitoring than previously and this naturally leads to increased reporting. It was also noted that there has been an increase in agriculture, which results in more nutrients reaching the Mediterranean and consequently more blooms. An additional point was made that routine monitoring programmes established over recent years have also led to the identification of a new species in a particular region.

This could either be as a result of the natural movement of water, or due to increased shipping and transfer through ballast water.

- *Is the mouse test enough for health protection purposes or would forms of advanced warning be useful?*

The discussion identified the additional techniques employed for public health protection purposes. It was recognized that there is the potential for remote sensing to play a role in the advanced warning of the possible bloom, but that this would not be sufficient for public health needs. There is a need for further development to integrate remotely sensed and *in situ* data. It would be desirable ultimately to phase out the mouse test completely.

- *How well is the integrated water column content correlated with remotely sensed near-surface concentration?*

This topic caused a considerable amount of debate. The first question to be considered was whether the composition of the water column was important to the appearance of algal blooms. This was acknowledged to be the case for lakes and closed systems, and also recognized as useful where there is an archive or long time series of *in situ* data. The role of shipborne lidar was discussed. A final issue was raised: how could remotely sensed data be used to determine different species and concentrations at different levels within the water column?

- *What combination of data/information is necessary for the monitoring of a toxic bloom?*
    - *Timescale*
    - *Cost*
    - *Priority areas*
    - *Frequency of acquisition*

The main limitations of remotely sensed data for the monitoring of a toxic bloom were identified as spatial scale and timescale, with the suggestion of additional data being provided from airborne sensors. However, remotely sensed data were seen as potentially useful for early warning within a particular area and with a known seasonal succession of species. Another suggestion was that satellite data could be used as a first warning, with aircraft being used to provide more site-specific and improved spectral, spatial and temporal resolution. It was noted that the frequency of monitoring would vary with the different species.

The following important but more general points were also made.

- There is a problem with legislation which is not always ‘scientific’ in terms of sampling methods and hence the impact on the consistency or otherwise of methods throughout Europe.
- The problem of anoxia was recognized, with it being noted that it would not be detected by current *in situ* monitoring techniques for public health purposes.
- It was noted that remotely sensed data would have obvious limitations where toxins occurred at very low cell counts.

5.4. *Workshop 4, Detection, monitoring and identification*

The fourth ABDMAP workshop was held in the Remote Sensing Laboratory, Department of Physical Geography, Stockholm University. The aim of the workshop programme was to give a broad view within the field of (harmful) algal blooms, while at the same time giving some presentations concentrating on specific topics. The workshop aimed to cover a number of topics related to remote sensing of the marine environment, and in particular the characteristics of cyanobacteria species and the vertical distribution of phytoplankton in the Baltic Sea. From the point of view of regional interest, the programme also included sessions on the monitoring activities around Sweden and neighbouring countries, including algal bloom research in the St Petersburg area. The use of remote sensing for monitoring HABs was also covered. A relatively new kind of method for algal bloom detection was also introduced at this meeting, namely the use of radar imaging as an additional tool for detecting and mapping the extent of blooms.

A total of 39 participants, representing various groups such as remote sensing scientists, people responsible for monitoring algal blooms, scientists from the biological/ecological field and others, participated in the workshop. An important part of the workshop was the group discussions, followed by presentations of the 'answers' to the questions that each group had to focus on. Most of the questions were based on 'speaker interests', as all speakers were requested to state one or several problems they wanted to have discussed. A number of discussion topics were given to the individual working groups of participants.

- *What are the conditions before a bloom? Are they detectable?*

It was a common opinion that there are a number of important parameters, such as water temperature and windspeed, that can be obtained by remote sensing techniques. These can provide useful input to predictive models, or may also give sufficient information to local experts who have the background knowledge and experiences from former events to make *ad hoc* predictions.

Some groups pointed out that bloom appearance is very location dependent, suggesting that prior conditions are important in the formation of a bloom. Some of the parameters can be directly derivable by remote sensing, while others can in some cases be inferred using other measurements.

- *Is it possible to differentiate between algal bloom species and, if so, how?*

The common opinion amongst all the groups was that broad group differentiation is possible, but individual species identification is not. Although it is theoretically possible using hyperspectral techniques, in practice it is much more complicated as many more factors become involved. The conclusion was thus that species differentiation is unlikely at the moment with current sensors. The use of fluorescence and UV light characteristics was also mentioned, since they can provide extra information.

A further point, regarding the impact on tourist locations, was made: the public does not really care which species is causing the blooms, so for some situations the species is not an important parameter.

- *How do we overcome spatial resolution limitations in some of the imagery?*

It was the general consensus that for large offshore blooms, the limited resolution is not a problem, but that for coastal zones better spatial resolution is needed. These types of higher resolution data are set to become available from the new very high spatial resolution satellites. Other techniques, such as airborne systems, could be used, but these do not provide the same coverage as satellite sensors. Alternatively, data can be incorporated from different sources. It was also recalled that satellites with higher spatial resolution give lower temporal resolution.

- *The possibilities of estimating biomass of surface algae*
  - *Demands for ground truth calibrations*
  - *Will future satellite systems improve the possibilities of quantitative estimations from space?*

There was a wide variety of opinion on this topic. Many of the problems associated with the use of remotely sensed data were identified, e.g. that it is possible to get very rough estimates of biomass, but large errors are commonplace since the surface layer thickness is not known. It was also noted that the determination of biomass as a function of depth is perhaps a more interesting problem. Clearly, direct sampling is still the most effective means of estimating the biomass.

However, it was noted that for Case 1 waters there is generally good correlation between chlorophyll-*a* and biomass and therefore chlorophyll retrieval algorithms can be used. Penetration of the water column is variable and problematic in Case 2 waters. Estimates from regions with similar bio-geographic properties can be made to derive generalized vertical models which can then be applied to surface measurements.

- *Can remotely sensed information be used to estimate regional differences in phytoplankton biomass and primary production?*

It was suggested that this should be possible with the right spectral band combination. However, there was uncertainty about the ability and extent to which plankton at depth can be detected; this depends on water clarity and depth of the plankton. Primary production measurements were considered less important for algal bloom detection and monitoring and models were thought to have large errors. However, time series data are considered invaluable for studying regional differences.

- *Is the penetration of the water column sufficient to cover the depth zone occupied by the majority of phytoplankton biomass?*

The light penetration depends on wavelength and turbidity. Green bands can penetrate up to 30–50 m in clear water. Colour sensors could give an estimate of biomass but may stop at the upper layer of the bloom and not penetrate further. However, it was noted that coastal blooms occur mostly in Case 2 water where suspended sediments dominate. The higher attenuation coefficient K gives the approximate depth to which a colour sensor measures $1/K$.

- *How would an efficient environmental monitoring programme be designed to integrate the need for detailed data on species composition with long-term biomass and productivity development using* in situ *as well as remote sensing techniques?*

For *in situ* measurements, it was suggested that a probe could be used for detecting species composition from spectral analysis (most blooms have a single dominant species), sampling for microscopic analysis, pigment analysis and autoanalysis of temperature and concentrations of suspended sediments and of all nutrients.

Satellite/airborne remote sensing data would then provide colour data for pigment, SST, slick detection from SAR (synthetic aperture radar), and visual observations (airborne platform). Measurements could also be done from/by ships/ferries/coastguards, etc. There would also be the need to make measurements from representative sites, which should be closer to the coast and in each basin. These should have a resolution of ca 50 m and a frequency of about every two days.

Other tools needed include a database of background knowledge and an integration tool.

- *Radar observations suggest that algal blooms result in slicks of oily films on the surface of the water; what controls the production and release of the active substances from algae?*

The surface film may be as little as one molecule thick and it is valuable to know if the substance is released during growth or as the algae die. For the moment there is no knowledge of oily exudates from phytoplankton. If the substance is released during growth it may serve as an indicator of blooms at depth. More surface-active material is needed for a slick for higher windspeeds. The windspeed should be 3–7 $m\,s^{-1}$ in order to see the slick in a SAR image. Clearly this is one topic that needs further research, both from the point of view of backscatter theory and determination of the exact cause of the oil production.

5.5. *Workshop 5, Earth observation data and products for inputs to biological models*

The fifth workshop was hosted by the Institute of Marine Biology of Crete, in Iraklion, Crete. This workshop paid special attention to the value of remote sensing data for modelling of algal blooms, but also considered the research and monitoring activities taking place around the Eastern Mediterranean and the Black Sea. This workshop was attended by 28 participants from a number of Mediterranean countries, as well as from the UK, France, Italy and Germany, bringing together an audience comprising remote sensing expertise and phytoplankton biological modelling expertise. The interchange of experience and know-how among researchers and end users from throughout Europe and non-European Mediterranean countries was implemented through a series of coordinated discussion sessions. A summary of the topics discussed follows:

- *How important are atmospheric corrections?*

It was noted that this depended upon the application, the requested accuracy and the height of the sensor, while atmospherically uncorrected images could also be of some interest. The difference in the absorption between AVHRR and SeaWiFS sensors concerning clouds was discussed. It was pointed out that the end users should at least check the importance of atmospheric correction on their data.

- *How site-specific are algorithms for chlorophyll and sediment estimation?*

Several problems were discussed, mainly the biomass primary production estimation from chlorophyll, the relation between surface production and vertical production, as well as the effectiveness of the chlorophyll estimation algorithms. For coastal waters it was mentioned that chlorophyll estimation is not realistic near shore and this is an area for further research.

- *What ancillary data are needed for the interpretation of ocean colour remotely sensed data?*

In order to develop better correction algorithms and primary production estimates, it was proposed that *in situ* sampling validations as well as concurrent collection of data related to wind, surface roughness, bathymetry, SST, O_3, aerosol climatology, etc. were required.

- *How could remotely sensed data improve model outputs?*

It was acknowledged that *in situ* and calibrated remotely sensed data could be used as input to models with relatively good accuracy. Basic models are based on SST data, which could help in an evaluation of bloom development.

- *Reflectance versus radiance?*

The need for this is dependent on the application being considered and the calibration procedure, but it was noted that reflectance seems to be more directly comparable to calibration data.

- *Definition of a plankton or algal bloom. What is the critical concentration?*

A threshold definition of phytoplankton concentration to determine if it is a bloom or not would need to take into consideration the geographical and hydrological conditions. The bloom is characterized by an exceptional growth relative to the background environment and usually by a change in dominant species.

- *What triggers a bloom? A model aspect*

Several parameters affect bloom development (such as light and nutrient gradients); however, it is difficult to isolate which is the trigger factor responsible for the bloom. Rapid algal bloom development is a combined result of an increase in algal reproductive rate and reduction in grazing rate. Any factor affecting the above biomass ratio could trigger the biological processes. Biological clocks and small-scale differences, however, make any prediction approaches difficult. Therefore the development and evaluation of models require long time series.

As a general conclusion from this workshop, it was noted that there is a definite role for remote sensing information as input to biological models, but that the full use of such data is yet to be implemented on a regular basis.

5.6. *Workshop 6, Détection des blooms d'algues: ABDMAP (Algal Bloom Detection Monitoring and Prediction)*

The sixth workshop was hosted by the Université du Littoral, Côte d'Opale, in Wimereux, France, in March 1999. The International Colloquium comprised three parallel workshops, and plenary opening and closing sessions. The other two workshops addressed:

- cross-border cooperation on the littoral and coastal space;
- remote sensing to littoral and coastal environment.

A total of 120 participants attended the international colloquium, with approximately equal numbers attending each workshop. Participants were mainly from northern Europe—especially France and the UK.

Given the very recent public launch of the Fifth Framework Progamme of the Commission, it was inevitable that much of the discussion centred on the future and on how the experience gained from the ABDMAP Concerted Action could be channelled into a successful follow-up within the Fifth Framework Programme of the European Commission. Topics discussed included the change of emphasis and sharpening of focus in the Fifth Framework Programme and the need to identify rather precisely the appropriate part or parts of the Programme that would be relevant to work on algal blooms. It was noted that there was no doubt that monitoring algal blooms in the coastal waters of Europe would be an ongoing important and serious task, and that the coastal areas are of undoubted importance within Europe far out of proportion to their actual geographical/cadastral areas.

5.7. *Workshop 7, ABDMAP review and focus on the Irish Sea*

This, the final ABDMAP workshop, aimed to review local (Irish Sea) blooms and state-of-the-art monitoring techniques (satellite, airborne and *in situ* techniques), and to review the ABDMAP Concerted Action in general.

Delegates from a wide range of local government agencies, local commercial organizations, central government agencies and commercial groups, as well as interested academics and research scientists from private and government institutions and universities were invited. Overall, 44 delegates from nine different countries, with interests ranging from public health issues and effects on tourism to the atmospheric correction of remotely sensed ocean colour data, attended the meeting. Working groups addressed two key questions and summarized their discussion for the meeting.

- *What are the priority issues for future research (next five years), from the end user perspective?*

A wide range of issues was discussed, concluding that considerable research remains to be done. The issues highlighted were as follows.

  - To improve spatial resolution, preferably without decreasing temporal resolution.
  - To improve atmospheric correction.
  - To standardize methodologies (e.g. for chlorophyll measurements).
  - To increase the quantity and quality of regional in-water data including *in situ* optical data.
  - To improve the perception of the importance of ocean colour and ABDMAP.
  - To improve the UK feedback system; encourage the use of near-real-time satellite data for monitoring and directing boats, etc.
  - To develop physico-biological bloom prediction models.
  - To assimilate remotely sensed data into models.
  - To develop a real-time bloom prediction service (like weather forecasting).
  - To be able clearly to distinguish parameters, e.g. chlorophyll, suspended particulate matter and yellow substances from ocean colour data.
  - To improve cloud cover detection and elimination.

The problems raised were as follows.

  - Toxic algae do not always form blooms and are often at very low concentrations.
  - Different users have different objectives and therefore require vastly different measurements, specifically the need for accurate versus relative chlorophyll measurements and the need for high spatial resolution at some locations (e.g. coastal zones) versus high temporal resolution.

- *If remotely sensed ocean colour data cannot give species information, what else is of importance?*

With species determination from remotely sensed ocean colour not feasible at present, the question of what else is of use to end users proved a difficult question. The major concern was to define end users, as their needs differ. Near-real-time data are important as even without species knowledge it alerts users to bloom conditions. To be able to react to bloom occurrences it is necessary to have fast access to remotely sensed data and local knowledge of the physical conditions to be able to determine the likely movement of the blooms. A database of past knowledge about blooms, where they occur and when, is essential to provide information on potential species. Knowledge of any limiting parameters (e.g. SST, nutrient concentrations, etc.) for bloom development is important.

The general discussion at this workshop raised many of the issues highlighted by the groups.

- End users are very important and need to be clearly identified along with their specific requirements. The scientific community needs a clearer idea of what the 'customer' wants. No average 'end user' requirements could be identified; each end user has different needs.
- Spatial resolution higher than that provided by SeaWiFS is needed for some locations, e.g. estuaries, and for certain applications. Higher spatial resolution must not result in a decrease in temporal coverage; daily imagery is needed. Cheaper (or free) Landsat imagery is needed; it was, however, noted that the price of Landsat data has now been substantially reduced. The cost benefit for increasing satellite sensor resolution, compared to the use of airborne sensors, was considered.
- More pure research is needed on phytoplankton species to look at the identification and distribution of their spores. Knowing the exact species is not necessary for many applications. The problems and interactions of different species in the marine environment are still not well understood.
- There is a need for more coordinated sampling, more *in situ* datasets with complementary remote sensing data for algorithm development and as input to models. This emphasized the need for the ABDMAP metadatabase and it was suggested that it should link in with other databases.
- The attenuation coefficient, K, was considered the single most useful parameter that can be derived from remotely sensed ocean colour data. Satellite imagery can provide measurements of photosynthetically active radiation (PAR) and of percentage cloud cover. PAR was highlighted as an important measurement for phytoplankton studies and for phytoplankton modelling.
- Existing one-dimensional models for predicting the onset of the spring/autumn blooms are as good as meteorological models, but a full predictive model for bloom events should be developed within the next 10 years. There are insufficient datasets available to test models. Global models are unlikely as conditions are highly regional. However, there was some optimism that pelagic phytoplankton bloom models may be able to predict blooms to family level e.g. diatom, dinoflagellate, etc.
- The problems of cloud cover on ocean colour imagery do not allow the continuous monitoring of blooms in European shelf seas. It was shown that the cloud algorithm for SeaWiFS is not very strict so useful information can be obtained under light cloud conditions. Real-time meteorological data are needed to improve the atmospheric corrections for SeaWiFS data.

The key points and recommendations from the Bangor ABDMAP meeting were as follows.

- The spatial resolution of current visible remote sensing systems is too coarse for coastal applications, although higher resolution data will need careful analysis with respect to the physical variability of the water.

- ◦ Improved definition/knowledge of end user requirements is needed to direct ocean colour research.
- ◦ The ABDMAP metadatabase is necessary to aid research into the use of ocean colour data for algal bloom detection, monitoring and mapping.

6. Information exchange and dissemination

6.1. *A metadatabase*

A part of the data management task within the ABDMAP project was the implementation of a metadatabase for those people or organizations interested in the study or monitoring of algal blooms in European waters. As part of this activity, the following tasks were carried out.

- Review of metadata formats and identification of relevant resource types.
- Review and assessment of other related database projects.
- Development of online internet resources (ABDMAP homepage).

A number of metadata standards have evolved to answer growing user requirements for ease in locating data which meet specific criteria, ease in determining the quality and value of these data and ease in accessing these data across different information systems. In this project we adopted the metadata standards defined by the CEO (1999).

The purpose of a metadatabase is not to hold all the possible relevant data on, in this case, algal blooms. Rather it is to provide an enquirer with information, for example for a given geographical location, about what data are available and where such data can be found. Thus the main role of the metadatabase within ABDMAP has been identified as the provision of an information source to aid in the study of algal blooms within European waters, with particular attention being paid to the role of EO data. In essence, the database should allow:

- EO researchers to locate *in situ* data sources as well as EO data sources;
- researchers interested in algal bloom prediction or modelling to acquire, as efficiently as possible, information on *in situ* and EO data sources, as well as algorithms or models used by others;
- researchers interested in water quality issues, etc. (the so-called 'user') to acquire information on the suitability and location of data sources and/or researchers/ institutes, that may be of use in their operational activities.

6.2. *Reports and publications*

The ABDMAP project was represented at the following conferences.

- VIII International Conference on Harmful Algae, held in Vigo, Spain, 25–29 June 1997.
- Ninth Australasian Remote Sensing and Photogrammetry Conference, held in Sydney, Australia, 20–24 July 1998.
- Fourth Pacific Ocean Remote Sensing Conference, PORSEC '98, held in Qingdao, China, 28–31 July 1998.
- Fifth International Conference on Remote Sensing for Marine and Coastal Environments, held in San Diego, California, 5–7 October 1998.
- EUROHAB workshop on Marine Harmful Algal Blooms: Research in Europe, held in Kalmar, Sweden, 5–7 November 1998.

The ABDMAP project was brought to the attention of the NASA SeaWiFS Science Team at two annual meetings of the Team to ensure that the relevant North American scientific community is kept aware of the European dimension to the use of ocean colour data from space. This is an important way of maintaining the visibility in North America of work funded on this topic by the European Commission.

The production of this Special Issue of the *International Journal of Remote Sensing* has been an activity of the ABDMAP project. It has attracted papers from many authors in a number of different countries. These have undergone the normal journal refereeing procedure with a number of papers accepted/accepted subject to minor revisions.

An end user questionnaire was developed for circulation throughout Europe and elsewhere. The questionnaire aimed to obtain detailed information relating to:

- ongoing algal bloom monitoring programmes;
- the extent to which EO data are used;
- the identification of those parameters that EO data can play a role in providing.

The results of the end user consultation provided input to the various ABDMAP workshops.

During this project a state-of-the-art review was compiled; this paper includes a considerable amount of material from that review.

7. Conclusions

The use of EO (remote sensing) data from space in connection with the study of algal blooms is almost entirely concerned with the use of the visible and near-infrared spectral bands, i.e. with ocean colour scanners. While there may be some evidence of algal blooms in thermal infrared data or in active microwave data, such data are not widely used in this connection. The spatial resolution of ocean colour scanners is often inadequate for studies of algal blooms in estuaries and inland water bodies. Remote sensing of ocean colour from space began in 1978 with the successful launch of NASA's CZCS. This was an experimental mission intended to last for only one year, but in fact it collected data from 1978 until 1986. For the next 10 years there were no other sources of ocean-colour data from space until the recent launch of MOS, OCTS and POLDER in 1996, SeaWiFS in 1997 and OCI in 1999. Several other ocean colour scanning systems are planned for launch in the near future.

7.1. *Relation to the ABDMAP project's objectives*

The main questions raised in this project were identified in §1.2 and are related to the *detection*, *monitoring* and *prediction* of algal blooms.

- Is it possible to use EO data to *predict* the appearance of an algal bloom?
- Is it possible to use EO data to *detect* a bloom?
- Is it possible to use EO data to *identify the biological species* present in a bloom?
- Is it possible to use EO data to *monitor the evolution* of a bloom?

To draw conclusions from this project we attempt to indicate some answers to these questions and then relate these answers to the objectives of the project.

7.1.1. *Is it possible to* predict *the appearance of an algal bloom?*

Given that the onset of a bloom represents a massive explosion in the population of a species of algae in an area where there is usually a background population present all the time, the onset depends very sensitively on a number of parameters, such as temperature, salinity, concentration of nutrients, etc. While one can build models involving the relevant parameters, it is not possible to obtain enough information about the values of all these parameters from EO data to be able to use such models for reliable prediction of blooms.

7.1.2. *Is it possible to use EO data to* detect *a bloom?*

The answer to this question is positive, subject to certain qualifications or restrictions, including the following.

- There needs to be an appropriate EO satellite in operation at the time in question.
- The satellite has to pass over the area in question at the appropriate time and the area must not be cloud covered.
- The user has to be able to obtain access to the data or information derived from the data.
- To be of use in practice the data must be made available to the user in near-real-time.
- The bloom to be studied must not be too small for the observation capabilities of the EO system.

7.1.3. *Is it possible to* identify the biological species *present in a bloom?*

The answer to this question is rather negative. One or two generalizations are, however, possible. Coccolithophores are sufficiently distinct that they can be distinguished from other features in EO data. Other generalizations may be able to be made regarding the likely group of species to which an observed bloom may belong, based on the spectral properties of the data or on background knowledge of the particular area or location in question. It is doubtful whether this situation would even be significantly improved with the advent of better spectral information from EO data from hyperspectral imaging systems in the future.

As a corollary to this question one can ask whether it is possible to detect toxicity of a bloom from EO data. This is even more difficult than species identification because there is no obvious indicator of toxicity in any parameter observable from space. And, moreover, even if species identification were possible, there is no unique correspondence between species and toxicity, i.e. a species may or may not be toxic depending on parameters such as concentration, age of the bloom, etc.

7.1.4. *Is it possible to* monitor the *evolution of a bloom?*

The answer to this question is positive, subject to the same qualifications and conditions as in §7.1.2 regarding detection of a bloom and to the further condition that:

- a time series of usable images is available over the period in question.

7.2. *Users' requirements*

Recurring issues from both the series of workshops and the response to the users' questionnaires included requirements for:

- high resolution data (spectral, spatial and temporal);
- data at an affordable price;
- access to dormant data sources and mechanisms for data exchange among parties;
- development of reliable algorithms for the analysis of EO data to determine marine parameters (in Case 1 and Case 2 waters and for different water bodies);
- integration of EO data into coastal information systems;
- integration of EO data into coastal management systems;
- near-real-time access to EO data.

7.3. *The project team's conclusions*

It was agreed that the ABDMAP Concerted Action had demonstrated the following.

(*a*) The need for further basic scientific work, particularly on the prediction of bloom occurrences. An essential part of this work will be assimilating time series that accurately document the occurrence and location of algal blooms. This will enable detailed knowledge of the typical species for a particular location and so support species identification using spectral characteristics, and also provide an aid for risk assessment purposes (e.g. risk in terms of toxic and other harmful/nuisance impacts).

(*b*) The need for the establishment of operational integrated detection and monitoring systems where remotely sensed data constitute one of many data sources. This is going to be necessary in order to establish the enhanced monitoring capability that will be required to cope with existing and increased environmental and human health legislation in the future.

(*c*) The need for the maintenance of a forum for the continued exchange of information and experiences among the responsible bodies in the various Member States of the European Union.

8. Recommendation

We would like to close with a recommendation to policy makers, such as the European Environmental Agency and the European Commission, concerned with water quality matters. This recommendation is as follows.

Bearing in mind that current data collection methods relating to algal blooms are based on *in situ* observations, which necessarily only give relatively fragmentary information, and bearing in mind the capability of EO methods to gather synoptic data over large areas on a regular and frequent basis, it is the clear recommendation of the ABDMAP Concerted Action project that future algal bloom monitoring programmes should take full account of the potential of EO data in conjunction with conventional data sources and ensure that their directives and recommendations recognize the European perspective.

It is to be hoped that this recommendation will come to the attention of such bodies and will be implemented by them.

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