Status and Plans for Satellite Ocean-Colour Missions: Considerations for Complementary Missions

Reports of the International Ocean-Colour Coordinating Group

REPORT NUMBER 2

IOCCG

An Affiliated Program of SCOR
An Associate Member of CEOS

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An Affiliated Program of the Scientific Committee on Oceanic Research (SCOR)
Supporting the Committee on Earth Observation Satellites (CEOS)

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Status and plans for Satellite Ocean-Colour Missions: Considerations for Complementary Missions.

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Contents

Executive Summary

This report explains the utility of ocean-colour data, summarizes technical requirements for global-scale, operational and scientific remote sensing of ocean colour in both Case 1 (open-ocean) and Case 2 (coastal) waters and addresses the issues of complementarity that arise whenever more than one sensor with similar capabilities is in orbit at the same time. The objective is to provide space agencies with the information necessary for them to begin developing an internationally-coordinated plan for the uninterrupted delivery of ocean-colour data into the indefinite future.

The Utility of Ocean-Colour Data

We recognize here three broad scientific applications of ocean-colour data. The first concerns the ocean carbon cycle, and the role of the ocean in climate change. It is therefore of profound significance in the response of governments and agencies to the Kyoto Protocol. A primary goal of ocean-colour remote sensing is to produce synoptic fields of chlorophyll pigment, an index of phytoplankton biomass. It is the single most important property of the marine ecosystem that we would like to measure at synoptic scales. Phytoplankton consume carbon dioxide in their basic nutrition (photosynthesis). On a global scale, marine phytoplankton consume fifty thousand million tonnes of carbon every year in a process referred to as primary production.

One of the aims of climate research in the ocean is to quantify this carbon flux, to understand how it is controlled and why it varies from year to year. This is the province of the marine programmes of the IGBP, and ocean-colour remote sensing plays an invaluable role in these programmes. It is used as the basis of a method to compute ocean primary production, and also to provide the chlorophyll fields that can be used to initiate and verify coupled, numerical models of the ocean and its embedded ecosystem. Looking to the future, it will be used in earth-observing programmes such as GOOS to detect changes in the structure and function of the ocean ecosystem that follow from the ensemble of forces that we refer to collectively as climate change.

A second application of ocean-colour data is to provide a synoptic, observational link between the development of the ocean ecosystem and the physics of the mixed layer. Because phytoplankton control the optical turbidity in most parts of the ocean, they control the manner in which the mixed layer heats up under the influence of the sun. Physical models of the mixed layer include a balance between the onset of stratification through heating and the erosion of stratification through turbulence. Optical turbidity is a key property in these models, and it can be delivered synoptically from ocean-colour remote sensing. Mixed-layer models seek to predict sea-surface temperature, critical for weather forecasting in maritime areas, especially in the tropics. Thus, ocean-colour data will be important in IGOS programmes such as GODAE, and will be important more widely in earth-observing programmes such as GOOS.

The third application of ocean-colour data that we mention here is the general area of coastal zone management, including fisheries management. One of the central questions in fisheries science today is the extent to which fluctuations in the biomass of exploited stocks can be accounted for by fluctuations in the ecosystem consequent upon variations in the large-scale circulation. It is a question that can be addressed only with the aid of a time series of synoptic views of the ocean ecosystem as supplied by ocean-colour remote sensing. One of the tragedies of modern biological oceanography is that, at a time when major fish stocks were failing around the world, there was no stream of ocean-colour data available that could have been utilized in discussion of these matters. Beyond fisheries issues, ocean-colour data are useful for many other aspects of coastal-zone management, for example the monitoring of harmful algal blooms and coastal pollution. These applications will become more important as population pressure on the coastal rim increases.

Principal Scales of Coverage

Ocean-colour data are usually discussed at two principal scales. These are: the global scale and the local scale.

- ❖ Global- (and regional-) scale data are collected with a resolution from 4 to 8 km. They are useful in questions pertaining to the planetary carbon cycle, and therefore to issues relevant to the Kyoto Protocol, to the IGBP, and to GOOS. For the most part, they refer to open-ocean or Case 1 waters.
- ❖ Local-scale data are collected with a resolution of 1 km or better. They are especially useful for coastal or Case 2 waters, and are of particular interest to programmes such as GLOBEC, LOICZ and HAB.

The requirements of typical applications at these two principal scales are different, and they will be treated sequentially in this report.

Principal Mission Types

Another way to classify ocean-colour initiatives is according to the mission type. The most fundamental differences are between operational missions that support government programmes (such as the meteorological satellites supporting weather-forecast centres), scientific research missions (such as OCTS and SeaWiFS) and proof-of-concept missions (CZCS). Again, the requirements of these three mission types are different, and the mission protocols have to take these differences into account.

Science requirements for global- and local-scale ocean-colour missions call for continuous, unbroken observations into the foreseeable future. Furthermore, there have been no operational missions to date for ocean colour, in the sense that there is one for sea surface temperature where the NOAA series has already reached number fourteen. As argued in this report and elsewhere (*e.g.* JGOFS Report No. 20, 1996), the need for continuous, global observations certainly exists. It can be said that, at present, ocean colour is in the process of maturing from experimental and research missions to operational missions.

Complementarity

We show that the requirements for ocean-colour measurements of the open ocean and the coastal zone are different, and thus complementarity has to be considered separately for each.

The requirements for global ocean observations are as follows : (1) global spatial coverage at a resolution of 4 to 8 km; (2) three to five day temporal resolution; and (3) a minimum band set that includes three channels in the visible and two in the near infrared with adequate spectral resolution and signal-to-noise ratio.

Except for temporal resolution, OCTS, POLDER, SeaWiFS, MODIS-AM, MERIS, GLI, and MODIS-PM each fulfil the requirements mentioned above. However, no single instrument operated on its own, is, or will be, capable of meeting the temporal resolution requirement. Based on OCTS and SeaWiFS experience, the coverage of one global instrument is strongly limited by sun glint and cloud cover (sun glint is not an issue for POLDER because of the multi-angle viewing capability of the instrument). The temporal resolution achieved by any one of the above instruments (except POLDER) is calculated to be only 15% per day at most (Gregg *et al.*, 1998). Thus we need to integrate data from several instruments on board different satellites. With three instruments we can observe 60% of the global ocean every four days.

From 2000-2005, ocean-colour data from GLI, POLDER, MODIS-AM, and MERIS need to be integrated to fulfil the temporal resolution requirement for global ocean observation. SeaWiFS will provide overlap during the first part of this five-year period and MODIS-PM will do likewise for the latter part. This scheme will have reasonable redundancy to protect against launch delays and operation failures. It will also give us observation data at different equatorial crossing times; *e.g.* 10h00 for MERIS and 13h30 for MODIS-PM (ascending).

The requirements for coastal monitoring are evolving and the combination of high spectral resolution, high spatial resolution (0.1 to 0.5 km) and frequent revisit are very difficult requirements to meet. In the 2000-2005 era, MODIS, MERIS and GLI will provide major advances in coastal water imaging and will meet many of the spectral and spatial requirements for Case 2 waters. The development of new algorithms will be possible from these sensors that are not possible from SeaWiFS. For example, we expect that algorithms to retrieve chlorophyll-*a* fluorescence (near 685 nm) will complement chlorophyll retrievals using conventional algorithms in phytoplankton-rich waters. Fluorescence algorithms are expected to be particularly helpful in Case 2 waters, in which the performance of conventional chlorophyll algorithms may be expected to deteriorate. However, the fluorescence algorithm is still experimental and it is imperative to consider alternatives. It is also imperative to collect as much *in situ* data as possible to establish and validate a universal Case 2 water algorithm(s).

For the post-2005 timeframe, multiple sensors with complementary technical specifications (including orbits) and with mission teams that coordinate calibration, validation, product generation and data delivery could provide international users with far more valuable data per unit cost than would uncoordinated missions. True complementarity requires cooperation among space agencies at the mission-planning stage. Clearly the ultimate responsibility for coordinating future missions rests with the space agencies, not with the IOCCG. The IOCCG is willing to assist the agencies, but lacks the mandate from them to coordinate detailed planning activities. For the present, the IOCCG's role is to provide advice (*e.g.* in the form of this, and other, reports) and as agency plans evolve, to provide an assessment of the missions (as was done for the pre-2005 timeframe outlined in Chapter 4). The IOCCG will revisit this important topic periodically as space agency plans develop.

The goals for post-2005 ocean-colour measurements from space are to provide, in a cost-effective way, continuous measurements on a regional and global scale and data sets improved with respect to geometrical, spectral and temporal performance. These goals will ensure: increased accuracy in the derivation of geophysical quantities in both the open oceans and the coastal zones; new products to improve the understanding of aquatic ecosystems in the coastal zone; capability for frequent and accurate water quality assessments; and the observation and quantitative analysis of special (and harmful) algal blooms.

Chapter 1

Introduction

One of the goals of the International Ocean-Colour Coordinating Group (IOCCG) is to advise space agencies on technical matters relating to present and future missions during which ocean-colour data will be collected. To this end, a series of reports is being prepared by the IOCCG dealing with key issues in the development of ocean-colour technology and its applications. The reports are the fruits of technical workshops, convened and sponsored by the IOCCG, attended by leading experts in the field and chaired by specialists of high authority.

The first of these reports (IOCCG, 1998) addressed the minimum spectral requirements for ocean-colour remote sensing in open-ocean (optical Case 1) waters, with the intention of specifying a common waveband set that would be carried on all future missions.

The present report, the second in the series, deals with the technical requirements for global-scale, operational and scientific remote sensing of ocean colour in both Case 1* and Case 2† waters. This report also addresses the issues of complementarity that arise whenever more than one sensor with similar capabilities is in orbit at the same time. The objective here is to provide space agencies with the information necessary for them to make an internationally-coordinated plan for the uninterrupted delivery of ocean-colour data into the foreseeable future. We present the principles and technical basis for addressing sensor complementarity and for designing an integrated programme of global ocean-colour observations that meets ocean-basin and coastal user requirements. We apply these to an analysis of the sensors currently scheduled for launch up to 2005. We address briefly the development of a strategy for post-2005 observations (where there is opportunity for international collaboration in development of an integrated global mission), and recommend that the development of such a strategy should be undertaken as a matter of urgency before the end of 1999.

For the purposes of this report, we distinguish between three general types of missions: operational, scientific/research and proof-of-concept (technical demonstration). Future commercial missions may

* Case 1 waters are those in which phytoplankton and their associated materials (such as debris, heterotrophic bacteria, larger heterotrophic organisms and autochthonous yellow substances) play a dominant role in determining the optical properties of the water body.

† Case 2 waters are those in which other substances, such as resuspended sediments, terrigenous particles, terrigenous yellow substances or anthropogenic materials, vary independently of phytoplankton concentration and play a dominant role in determining the optical properties of the water body.

have similar technical requirements as operational or scientific missions but are not specifically considered in this report. The primary goal of operational missions, such as the various types of weather satellites supporting weather forecast centres, is to provide data to government agencies. Scientific or research missions, such as SeaWiFS and OCTS, support scientific programmes, *e.g.* Joint Global Ocean Flux Study (JGOFS). Proof-of-concept missions are used by space agencies to demonstrate a new technology or a new capability. Some missions serve multiple purposes (*e.g.* the Advanced Very High Resolution Radiometer, AVHRR, is carried by an operational satellite but the data are also used extensively for scientific research), but the technical requirements are generally driven by the primary user group.

A further motivation for this report is the emerging context of an Integrated Global Observing Strategy (IGOS). The aims of IGOS parallel, for a rich array of geophysical variables, those that the IOCCG has already established for ocean colour. One of the goals is to define a combination of missions, through international collaboration, that will meet the requirements of continuous global and temporal coverage in the most cost-effective manner possible.

Within the arena of ocean biology, where the IGOS interests are looked after by the IOCCG, the longer-term deliverable is the development of a strategy for the implementation of a global-scale, blended, internally consistent, spatially complete and temporally uninterrupted set of ocean-colour data achieved in the most efficient, economical and coordinated manner.

A principal conclusion of this report is that one satellite alone will be unable to meet all of these requirements: more than one satellite is necessary. Furthermore, as we shall show later in this report, we need more than one satellite in orbit at the same time to provide global coverage at the time scales desirable for many applications. The need then arises for strong international cooperation and coordination, and it is in this spirit that the IOCCG was born.

Chapter 2

Utility of Ocean-Colour Data

Uses for satellite ocean-colour data can be categorized within three broad thematic areas: (1) quantifying ocean carbon flux, understanding how it is controlled and why it varies from year to year; (2) providing a synoptic, observational link between the development of the ocean ecosystem and the physics of the mixed layer; and (3) assisting with the scientific analysis and management of the coastal zone, including fisheries management. Theme 1 is generally associated with basin-scale analyses and modelling, whereas Theme 3 has a more local- to regional-scale focus. Theme 2 receives equal emphasis at basin- to global-scales.

2.1 Ocean Carbon Flux

The principal users of satellite-derived, ocean-basin to global-scale phytoplankton chlorophyll fields are the global-change programmes, particularly those such as JGOFS that are interested in ocean biogeochemical processes and their links to the global carbon cycle (JGOFS Report No. 20, 1996). These programmes need long-term data sets, including satellite data sets, to quantify the effects of periodic climate phenomena such as El Niño, and to separate the periodic effects from those that may be occurring in response to human-induced changes to the ocean environment, including permanent climate changes.

Biological processes affect net air-sea CO_2 fluxes in two fundamental ways. First, photosynthesis removes CO_2 from surface waters and transforms it into organic carbon, initially bound within phytoplankton (microscopic plants) and other particles. Second, a significant percentage of organic particles formed within surface waters eventually sink through the main ocean thermocline. Sinking particles move carbon against vertical gradients of density and CO_2 concentration. The long-term operation of this "biological pump" is one of the principal reasons why the concentration of total CO_2 (TCO_2, which is CO_2 + CO_3 + HCO_3) is generally much higher in deep waters than in surface waters. Recent models emphasize the importance of both biological and physical processes for determining oceanic CO_2 uptake during the next century and its relation to global warming (Sarmiento *et al.*, 1998).

Satellite ocean-colour sensors are now the standard (indeed the only) tool to determine ocean-basin to global distributions of phytoplankton chlorophyll-*a*. Ocean primary production (CO_2 uptake by plants) cannot be directly measured from space, but is calculated from chlorophyll-*a* concentration. Model studies show that global productivity calculations are very sensitive to the input surface chlorophyll fields (Platt and Sathyendranath, 1988;

Behrenfeld and Falkowski, 1997; Field *et al.*, 1998), and thus satellite ocean-colour imagery is very important for accurate calculations of the mean and time-varying components of the global distribution of ocean primary production. Recent satellite-based estimates of marine and terrestrial primary production show that each contributes equally to global productivity (Field *et al.*, 1998).

2.2. Ocean Biology and Upper Ocean Processes

Phytoplankton and other particles absorb heat in the upper ocean which in some circumstances can be an important term in ocean heat budgets. Ocean-colour images are being used in upper ocean heat flux calculations. In regions such as the Arabian Sea (Sathyendranath *et al.*, 1991) and the Equatorial Pacific (Lewis *et al.*, 1990), this new approach makes a significant difference to the computed heat flux, as well as the vertical distribution of heat in the upper ocean. Ocean-colour imagery is the only source of biological information routinely available on a global basis and is thus one of the few sources of information that can be used to validate phytoplankton distributions predicted by regional- to global-scale numerical models. To improve the forecasting ability of ocean simulations, satellite-derived chlorophyll fields can be directly assimilated into numerical models using data insertion and adjoint methods, and early results are encouraging (Hofmann and Lascara, 1998).

Ocean-colour imagery is also used directly to observe the effects of climate and other large-scale phenomena, *e.g.* El Niño, on ocean basin-scale distributions of phytoplankton chlorophyll (Fiedler, 1984; Feldman *et al.,* 1984). This satellite capability augments and enhances *in situ* observation programmes by providing a very broad perspective in which to interpret detailed *in situ* observations from a few locations. The 1997/98 El Niño provided an excellent example of the need for multiple satellite ocean-colour sensors, and the importance of knowing how their signals are related. This most recent and very intense El Niño began while OCTS was in operation, however the maximum effects reached North America following the demise of OCTS and prior to the beginning of data collection by SeaWiFS. The documentation and quantification of El Niño's effect on surface chlorophyll fields in the Pacific, and possibly other ocean basins, therefore requires observations from two different satellite sensors. As human activity continues to alter the environment, some of the effects may be observable with a series of satellite ocean-colour sensors operating over a decade or more. For example, human-induced transfer of nitrogen (the production-limiting nutrient in the ocean) from the land, through rivers and the atmosphere, is a significant source of new nitrogen in the ocean (Cornell *et al.*, 1995). Over decadal time scales, this nitrogen flux to the ocean may have observable effects on the productivity and biomass of coastal and open-ocean phytoplankton.

2.3 Scientific Analysis and Management of the Coastal Zone

The coastal environment is traditionally a centre of important economic activity, exchange and settlement, and as such, is exposed to increasing human pressure as a result of activities such as tourism, agriculture, industries and fisheries. Improved understanding of the impact of individual coastal users and of natural events on the overall ecosystem will facilitate integrated planning and a better coordination of these activities. The LOICZ programme, one of the IGBP core-projects, was established in 1993 to provide a sound scientific basis for future, integrated management of coastal areas, on a sustainable basis (Pernetta and Milliman, 1995).

Increased concerns about the rapid and negative changes of coastal areas have highlighted the necessity for the development of integrated systems for research and operational use in monitoring the resources and processes in coastal waters. There is a strong consensus that earth observation data, in particular satellite ocean-colour data, could play a key role in providing information on water-quality parameters, thus complementing conventional sampling techniques to resolve specific environmental problems at adequate space-time resolutions. Examples are given below of some prevalent sources of environmental impact on the coastal zone.

2.3.1 Human-induced activities

Urban/Industrial expansion

Economic and related social development may have severe implications for coastal ecosystems, the shoreline and seabed morphology, including possible modifications of the physical and chemical properties of the water and the diversity of marine organisms.

Tourism

Uncontrolled or poorly-planned tourism development may severely damage the ecosystem in many ways, *e.g.* through pollution of marine waters (insufficient treatment of sewage) and beach erosion (construction of hotel facilities). Tourism may also prove to be detrimental to specific coastal environments such as mangrove forests and coral reefs.

Fisheries

More than 98% of the world's catch of marine species is taken within 300 km of the coastline, and more than half of the total biological production of the ocean takes place in that zone. Effective conservation and sustainable management of these fisheries are needed at national and international levels so that fish stocks can continue to meet global nutritional needs.

Agriculture

In many coastal areas, a considerable increase in the concentration of nutrients in coastal waters has been recorded. A major source of these nutrients is agriculture and intensive livestock-farming, which release chemicals into drainage basins from the use of fertilizers and pesticides. Nutrient enrichment (*i.e.* eutrophication) of the waters stimulates the growth of phytoplankton, leading, in certain circumstances, to the phenomenon of algal blooms and to anoxia in the lower part of the water column with destruction of the benthic fauna and flora.

2.3.2 Natural events

Mucilaginous waters

The mucilage phenomenon is represented by the appearance of a gelatinous material suspended in marine waters. This substance (consisting of polysaccharides secreted by unicellular algae in response to meteorological conditions) aggregates to form extensive floating patches shaped and driven by local winds and currents. Such phenomena have severe repercussions on the regional tourist industry and fisheries.

Toxic blooms

Many parts of the world's ocean, and particularly coastal waters, are subject to recurrent outbreaks of "harmful algal blooms" triggered by the combined effect of particular meteorological forcing and nutrient fields. Negative impacts of these exceptional blooms (as opposed to the annual "spring bloom") are associated with the presence of toxins secreted by various species of dinoflagellates (so-called red tides), diatoms or cyanobacteria.

Erosion/sediment transport

Erosion or modification of the shoreline is often associated with changes in the sediment load of the water column, which is redistributed from one place to another or derived directly from river run-off.

2.3.3 Monitoring techniques

With growing appreciation of the need for sustainable management of coastal resources, there is a pressing requirement for the development of quantitative, and cost-effective methodologies to detect and characterize both long-term changes and short-term events in the coastal environment.

Monitoring water quality

Current operational information on the quality of coastal waters is derived largely from surface measurements (*e.g.* buoys, ships) that are used either directly to monitor the water state or for integration into local predictive models. This information is expensive to collect and is thus usually severely limited, both temporally and spatially. Over the past few years, scientific investigations have demonstrated the ability of satellite data to provide water quality information through measurements of ocean colour (Holligan *et al.*, 1983; Dupouy *et al.*, 1988; Tassan, 1993; Sathyendranath *et al.*, 1997).

Fishery information

Recent advances in data acquisition systems, analysis methods and communication technologies have promoted the use of satellite data in the field of fisheries for both near-real-time support of the day-to-day fishing activities, and in the analysis of the decadal trends in fish populations. In several countries, expert systems have been developed to support the daily operation of fishing vessels in coastal areas (Sugimoto and Tameishi, 1992). Another fishery issue is related to major collapses of fish populations which are observed around the world at intervals of several years. Between 1994 and 1996, a drastic reduction of commercially-important clupeoid stocks occurred in major fishing grounds in spite of the application of sound management principles. According to recent evidence (Pauly and Christensen, 1995; Pauly *et al.*, 1998), the failure to predict such decadal trends in fish stocks can be attributed to a systematic under-estimation of the role of the environment and the pelagic ecosystem in recruitment models.

The advent of instruments for remote sensing of important ecosystem properties, *e.g.* phytoplankton biomass and primary productivity as derived from ocean-colour data, at higher scale resolution than from ship operations, offers the possibility of improving our understanding of the relationship between ecosystem factors and fish recruitment.

Chapter 3

Technical Requirements for Satellite Ocean-Colour Sensors

Technical components of scientific and operational satellite ocean-colour missions must include:

(1) sensors with appropriate specifications including the number and placement of spectral bands, signal-to-noise performance and footprint/swath characteristics to meet coverage requirements;

(2) calibration programmes to ensure sensor stability or to establish post-launch changes to the initial calibration;

(3) appropriate algorithms to calculate the data products of interest to scientists and managers;

(4) validation programmes to demonstrate that the data products actually meet mission objectives; and

(5) mechanisms for timely delivery of data products to the users.

The purpose of this chapter is to summarize some of the key requirements within the first criterion as a lead-in to Chapter 4, which will present an assessment of data expected from multiple satellite missions in the 2000-2005 timeframe. In particular, we show how requirements for observing coastal waters can be very different from those for open-ocean coverage. The four other criteria, which are of equal importance to operational and scientific users, may be the subject of future IOCCG reports.

The IOCCG is primarily involved with operational and scientific missions that meet the five criteria listed above but also recognizes that technical demonstration or proof-of-concept projects are of interest to national space programmes. Ocean-colour sensors are particularly attractive for technical demonstration projects as the sensors are relatively easy and inexpensive to build and launch. NASA's Coastal Zone Color Scanner (CZCS) experience showed, however, that data from technical demonstration or proof-of-concept missions are of little scientific use unless and until all five of the criteria given above are met (CZCS was a proof-of-concept mission, but about ten years after launch, NASA processed, archived and distributed the imagery as a research data set). The IOCCG is willing to help national space programmes meet objectives for proof-of-concept missions but at the same time, is also concerned that these missions are not confused with those that meet all of the five mission criteria given above. Thus, missions for technical demonstrations or proof-of-concept are not included in the analyses of Chapter 4.

3.1 Technical Requirements for Open-Ocean, Global Missions

IOCCG Report No. 1 (1998) discussed the minimum requirements for ocean-colour measurements in the open ocean, and we provide only a brief summary here.

3.1.1. Spatial and temporal requirements

Global change programmes are primarily focused on time scales ranging from seasonal to inter-annual, and spatial scales encompassing those of the larger ocean eddies to the global ocean. Spatial and temporal resolution requirements for ocean-colour sensors are driven by the scales at which biological processes operate in the ocean, as well as by practical constraints. Seven- to ten-day average chlorophyll fields will generally resolve seasonal biological phenomena such as phytoplankton blooms. However, since an "average" requires at least two measurements, an appropriate goal is to obtain global ocean coverage every three to five days.

Pixel resolution of 4 km is an oft-stated specification for global coverage. This specification for ocean-colour missions was chosen initially to be consistent with the Sea Surface Temperature (SST) Global Area Coverage (GAC) data product derived from the AVHRR sensors, as direct comparison between SST and chlorophyll fields has much scientific value. There is another good scientific argument for 4- to 5-km pixel resolution relevant to initialization, validation and assimilation procedures for numerical models. Current global, eddy-resolving models often use 20-km (0.2 degrees) grid spacing, and basic statistics suggest that initialization and validation fields, including chlorophyll-*a* fields, for these models should be collected with at least two times finer spatial resolution than the model grid spacing. Thus, 10-km pixels should be the minimum spatial resolution for current sensors, and assuming increasing model grid resolution to 0.1 degree (10 km) in the near future, 4- to 5-km pixels for global coverage are a reasonable requirement for sensors during the next decade.

3.1.2 Spectral requirements

Spectral resolution requirements derive from the need effectively to remove atmospheric components of the total signal acquired by a satellite, as well as the need to compute an accurate representation of biological products, primarily chlorophyll, from spectral radiance emanating from the ocean. Atmospheric contributions to top-of-the-atmosphere (TOA) radiance involve absorbing gases, molecular scattering, and particle (aerosol) scattering and absorption. The absorbing gas and molecular scattering components are eliminated using ancillary information about the distribution of optically-active atmospheric constituents (*e.g.*, ozone, water vapour, pressure) and detailed radiative transfer calculations. Aerosol scattering and absorption must be determined from the ocean-colour sensor itself, since no other ancillary information about their distribution and properties is available routinely at global scale. Theoretical and empirical analyses of ocean colour have shown that at least two bands located in the near-infrared region of the solar spectrum are required to provide the aerosol radiative properties necessary for ocean-colour retrievals. At the same time, avoidance of water vapour and oxygen absorption is desirable to simplify the problem of aerosol characterization. Consequently, a band located between 855 and 890 nm, and

Table 1. *Band centres and bandwidths required, as a minimum, for high quality observation of biological variables from remote sensing.*

Band Centre	Bandwidth	Purpose
438-448 nm	20 nm	chl (low-medium concentration)
485-495 nm	20 nm	chl (medium-high concentration)
550-565 nm	30 nm	chl (all concentrations/sediment turbidity)
744-757 nm	40 nm	aerosol characterization
855-890 nm	40 nm	aerosol characterization

another band located between 744 and 757 nm are considered the minimum for atmospheric correction (IOCCG, 1998). Additional bands between 704 and 713 nm, and between 1024 and 1064 nm are desirable to help separate the aerosol effects from those of foam and to provide a more reliable extrapolation of aerosol characteristics into the visible region.

Additional bands are required to determine the abundance and distribution of key oceanic biological parameters, primarily chlorophyll or pigment, after atmospheric correction. A minimum set of three bands has been shown (IOCCG, 1998) to be necessary to achieve these goals (Table 1). Although 20-nm bandwidths are the minimum requirement for visible bands, 10 nm is desirable to gather specific information about pigment composition (IOCCG, 1998).

3.1.3. Global observational requirements

As discussed above, a global observation of the ocean every three to five days is an appropriate target for ocean-colour measurements supporting studies of global ocean biogeochemical cycles and climate. Unfortunately, remote observations of the ocean surface in the visible and near-infrared are impacted by sun glint, which serves to confound accurate retrievals of biological products, or by clouds, which obscure surface observations entirely. In fact, a single ocean-colour satellite can observe only about 15% of the ocean in one day and about 40% in four days (Gregg and Patt, 1994). Multiple satellites can greatly improve the overall coverage in these short time scales. Two satellites improve the daily ocean coverage to about 20%, and three to about 23% (Figure 1). This represents coverage improvements of approximately 30% and 50% respectively over that achieved by a single satellite. Addition of more satellites improves the coverage only marginally over the combined three-satellite case. Similar coverage improvements occur if observations are aggregated over four days, resulting in a maximum of about 60% ocean coverage with three satellites (Gregg *et al.*, 1998). These coverage improvements do not take into consideration orbit phasing and node crossing selection that can further improve the combined coverage. Given the limitations of ocean surface viewing, three global satellites operating simultaneously are considered the minimum requirement to obtain the large scale observations necessary to understand the role of biological processes

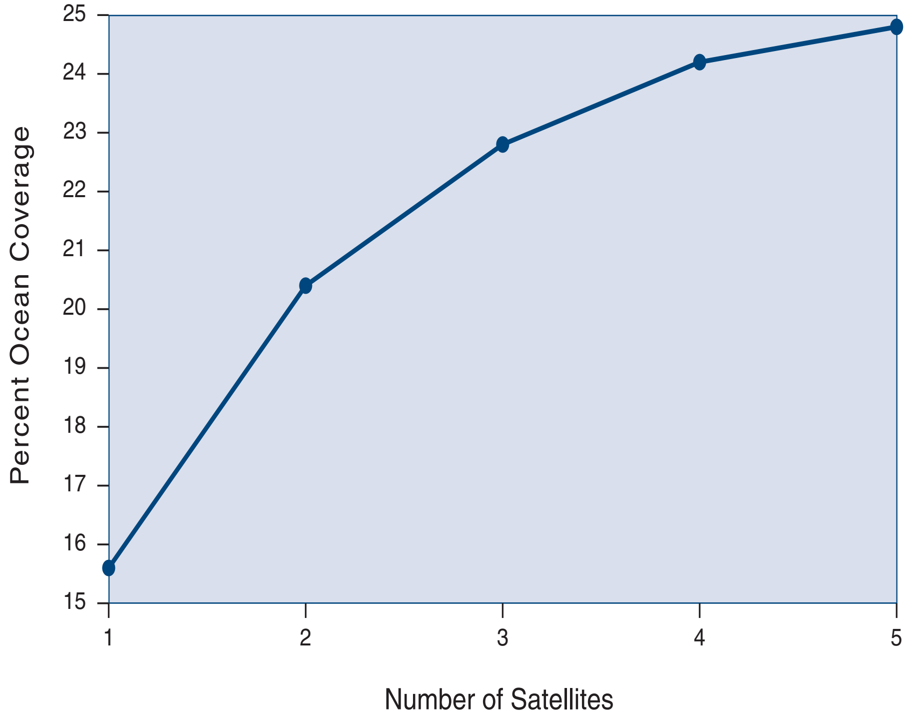

Figure 1. *Combined ocean coverage (in percent) by multiple satellites of the same design for one day. The satellite/sensor is SeaWiFS-type: noon descending node, 705 km altitude, scan width 45°, with a tilt capability. The satellite orbits differ only in the mean anomaly, which is set to produce average combined coverage. In this analysis, sun glint and clouds obscure observations of the ocean surface, producing the low estimates of ocean coverage. Sun glint is computed from climatological wind speeds as a function of viewing and solar geometry with respect to the satellite orbit. The sun-glint threshold is set to about four times the SeaWiFS Noise Equivalent Delta Radiance (NEΔL). This is an extreme estimate of sun glint contamination. However, sun glint can confuse the determination of aerosol characteristics, especially when the aerosol radiative characteristics are very different from those of sun glint, which may cause significant errors in chlorophyll retrieval. In the context of using data from multiple satellites, such possible errors need to be identified so they can be eliminated from the merged data set. Thus this estimate of sun glint supports the multi-mission application. Clouds are derived from global six-year climatology.*

in the global context. Wise orbit selection can improve the coverage even further.

3.2 Technical Requirements for Coastal Applications

The coastal applications described in Chapter 2 impose demanding requirements on ocean-colour sensors for spatial and temporal coverage, spectral resolution and signal-to-noise ratio (SNR). The community has not had experience with satellite sensors designed specifically for coastal ocean-colour applications. Most proposed coastal ocean-colour products are experimental, and development to date has been based on airborne missions. This situation will change in the near future, with the launch of sensors, such as the Medium Resolution Imaging Spectrometer (MERIS), that provide both spectral and spatial resolution designed for coastal products.

3.2.1 Spatial and temporal requirements

Effective imaging of coastal waters generally requires more rigorous temporal and spatial coverage than is necessary for the global ocean. Thus, coastal requirements are only partially met by the current generation of satellites. One of the more important sources of variability in continental shelf and slope waters is “events” occurring every two to ten days, generally in response to wind forcing. Thus, one-day coverage is a minimum requirement for resolving the event time scale, but is not routinely achievable given mean cloud coverage statistics for most regions. Tidal energy dissipation is also an important process affecting biological productivity of coastal waters, and its importance generally increases inversely with water depth. In many parts of the world, mixing and advection in near-shore and estuarine waters are dominated by tidal currents. Multiple observations during a single day are required directly to observe tidal signals, but this is very difficult or impossible to achieve with the current generation of polar-orbiting, non-pointable satellites. New technologies and approaches will be required for direct observation of changes during a single tidal cycle (see Section 3.4).

With the exception of frontal regions, middle to outer shelf and continental-slope waters are covered reasonably well with 1-km pixels. However, 1-km pixels are inadequate for near-shore and estuarine waters. Some important applications, *e.g.* imaging of the bottom in optically-shallow waters, require pixel resolution of 10 m or less. Such high spatial resolution (with appropriate spectral and SNR requirements), although theoretically possible from satellites, is probably not practical in the foreseeable future (although aircraft sensors such as AVIRIS can meet or exceed this requirement). However, imagery with 0.1- to 0.5-km pixels will provide useful scientific information for most bays and estuaries and is a realistic goal for the next decade (*e.g.* MERIS will have 0.3-km pixels).

3.2.2 Spectral requirements

Coastal or Case 2 waters are characterized by the independent variation of concentrations of optically-important constituents, especially chlorophyll pigments, yellow substance (gelbstoff) and suspended sediments. The inherent optical properties of these constituents, especially suspended sediments, may also vary in space and time. As a result, the simple Case 1 band-ratio algorithms, which depend on the existence of a one-parameter family of water types indexed by chlorophyll concentration, are not applicable. Additional spectral information is needed to estimate independently concentrations of chlorophyll and the other constituents which also constitute important products for coastal zone management applications.

In IOCCG Report No. 1 (1998) the sensor spectral characteristics needed to resolve coastal zone constituents are discussed. The report recommends adding a spectral band in the blue (around 410 nm) to the minimum Case 1 bands (see Chapter 3), to separate the effects of gelbstoff absorption, which increases exponentially at short wavelengths, from chlorophyll absorption, which peaks around 440 nm. The report also presents compelling arguments for increasing spectral resolution further. Because of the strong non-linear interactions among the constituents, researchers have turned increasingly to semi-analytic or model inversion techniques, which estimate constituent concentrations simultaneously by fitting reflectance models to water-leaving radiance spectra. These inverse techniques are sensitive both to observation errors in radiance estimates and to failure in model assumptions, and additional spectral bands can be used to reduce or flag these errors.

Algorithms that estimate chlorophyll by measuring sun-induced fluorescence at 680 nm avoid the variable effect of other in-water constituents on absorption and scattering. This technique makes use of the passive fluorescence emission of chlorophyll-*a* centred around 685 nm. The height of the fluorescence signal is measured relative to a baseline which is determined using two channels on either side of the emission peak (*e.g.* 665 and 710 nm), or relative to a nearby single band (*e.g.* 667 nm for MODIS). The fluorescence technique seems to be more practical at elevated chlorophyll concentrations which are more common in coastal waters (see Section 3.3 for further details regarding this technique). However, new results suggest that fluorescence detection may also be feasible in oligotrophic waters (Babin *et al.*, 1996).

Work is continuing on algorithms for distinguishing different kinds of phytoplankton pigments, particularly where these are associated with harmful algal blooms. For example, cyanobacterial blooms may be distinguished using the phycobilin absorption peaks in the 480 – 560 nm range. Again, these methods are more likely to be practical at bloom concentrations.

Water turbidity is also of interest to coastal scientists and managers. It has been proposed that a band around 620 nm could be used to help to quantify water turbidity.

More spectral bands may be required of future sensors, as coastal-zone managers would like to use ocean-colour sensors to monitor changes in cover and state of benthic habitat. This application requires algorithms which resolve and separate the contributions of in-water constituents and bottom reflectance to water-leaving radiance spectra.

Atmospheric correction in turbid coastal waters is complicated by the occurrence of non-zero water-leaving radiance beyond 700 nm. Aerosol correction then requires either additional channels in the near-infrared (NIR), and/or the use of inverse techniques to estimate simultaneously in-water constituents and aerosols.

Of the next generation of ocean-colour sensors, MODIS, MERIS and GLI provide the 660–680 nm band pair or the 660-680-710 triplet needed for fluorescence-based chlorophyll measurements (IOCCG, 1998). MERIS and GLI offer a 620 nm band for suspended sediment, and GLI is almost hyperspectral, with twelve 10-nm spectral bands from 380 nm to 680 nm. MERIS and GLI provide three NIR bands for atmospheric correction. Proposed new high-resolution hyperspectral sensors such as the Australian Resource Information and Environmental Satellite (ARIES) and the Naval EarthMap Observer (NEMO) will provide contiguous 10- or 20-nm bands throughout the visible and NIR region.

3.2.3 Observational requirements for global coastal waters

By comparison with open-ocean applications, coastal applications typically involve phenomena that vary on shorter space and time scales. Demands for simultaneously increased spatial and temporal resolution ultimately lead to unachievable data volumes and/or sensor and satellite characteristics. A scenario for meeting all of the requirements for ocean-colour measurements over coastal waters has not been developed. In particular the combination of high spectral resolution, high spatial resolution (0.1 to 0.5 km) and frequent revisit is a very difficult set of requirements to meet, unless cost is not an issue. Nevertheless, beginning in 2000/2001, the combination of MERIS and GLI should provide a major advance in coastal water imaging, as both sensors have extensive band sets, and MERIS can acquire data at 0.3-km pixel resolution. There are several proposed sampling strategies suitable for different applications.

Broad-swath, ocean-colour scanners such as SeaWiFS, MODIS, MERIS and GLI provide about 1-km resolution, with potential for global coverage on time scales of a few days (see Chapter 4), appropriate for processes at scales of continental shelves and coastal seas. Global (coastal) products at 1-km resolution are required for studies of land-ocean interactions and their role in global change (*e.g.* the LOICZ programme). The achieved coverage at 1 km depends in practice on LAC ground station coverage in the case of SeaWiFS, and on post-processing capability for the others, which have on-board storage at this resolution. MERIS is particularly attractive, as it offers increased spatial resolution (0.3 km) while retaining a broad swath.

3.3 Technical Requirements for New and Emerging Applications of Ocean-Colour Data

Clearly the technological requirements of an ocean-colour satellite are tied intimately with the applications envisaged. Up to now, we have discussed primarily the technical requirements for retrieval of chlorophyll-*a* concentrations in coastal and open-ocean waters using algorithms that rely on phytoplankton absorption in the blue and green parts of the spectrum. However, there is an increasing awareness that ocean-colour data can also be used to monitor other properties of phytoplankton. For example, there are plans underway to monitor phytoplankton fluorescence in the red part of the spectrum (see Section 3.2.2). Clearly, sensors designed to monitor chlorophyll fluorescence require bands in the red part of the spectrum in addition to those in the blue-green. Sensors with fluorescence capability are expected to provide information in waters with relatively high concentrations of phytoplankton biomass, whether it be in Case 1 or Case 2 waters. Hence, this type of sensor will straddle both types of applications. It is, however, important to recognize that monitoring fluorescence by chlorophyll-*a* is not expected to provide a duplicate measurement of chlorophyll-*a* concentration, but to provide complementary information. In this section, we examine how sensors with fluorescence detection capabilities will complement measurements of chlorophyll-*a* concentrations using more conventional approaches.

Conventional ocean-colour sensors have wavebands that have been selected to monitor changes in water-leaving radiances in the blue-green part of the spectrum. These changes are associated typically with variations in phytoplankton absorption, and algorithms in use today convert these changes to quantitative estimates of the main phytoplankton pigment, chlorophyll-*a*. Some of the newer sensors scheduled to be launched in the near future, such as MODIS, MERIS and GLI, have the 660-680 nm band pairs required to monitor the phytoplankton fluorescence in the red part of the spectrum (IOCCG, 1998). This is an experimental approach, in the sense that the basis of these plans is aircraft remote-sensing experiments (Gower, 1980; Gower and Borstad, 1990), in which chlorophyll fluorescence was successfully calibrated against chlorophyll-*a* concentration, such that the fluorescence signal could be used to map chlorophyll-*a* concentration. At first glance, it may appear that ocean-colour data in the blue-green part of the spectrum, and in the red part of the spectrum yield the same result. A closer examination, however, reveals that these two techniques do not necessarily yield the same information, but are complementary in many ways. The main differences between the two techniques are elaborated below.

3.3.1 Technical differences between measurements of chlorophyll concentration and chlorophyll fluorescence

Both phytoplankton absorption per unit chlorophyll-*a* concentration, and fluorescence per unit chlorophyll-*a* concentration are subject to certain variability in the natural environment, and so the algorithms for retrieval of these quantities require calibration against *in situ* measurements of pigment concentrations. Provided such calibrations exist, both methods can be used to monitor phytoplankton concentration. Nevertheless, one may anticipate several differences in the performances of the two techniques, as described below. The comparisons are also summarized in Table 2.

- Phytoplankton absorption influences water-leaving radiance in a non-linear fashion. Although the relationship between fluorescence and chlorophyll-*a* is often linear at local scales, non-linear relationships have also been observed (Kishino *et al.*, 1984; Karabashev, 1998) and the relationship is neither universal nor stable.

- Absorption-based signals are a decreasing function of chlorophyll-*a* (in the sense that the water-leaving radiance in the blue decreases with increasing phytoplankton concentration), whereas fluorescence increases with chlorophyll-*a*.

- Algorithms that depend on phytoplankton absorption are very sensitive to changes in pigment concentration at low phytoplankton concentrations (*e.g.*, in the concentration range of 0.1 to 1 mg m^{-3}), when both water and phytoplankton compete in the absorption process. At such concentrations, the fluorescence signal is hardly detectable. On the other hand, fluorescence algorithms are most effective at high pigment concentrations, when the absorption-based algorithms become less efficient, as the signal in the blue part of the spectrum drops below the limits of detection because of high absorption by phytoplankton. On a cautionary note, it must be mentioned that the fluorescence signal may saturate at high chlorophyll-*a* concentrations (Kishino *et al.*, 1984).

- Other substances such as coloured dissolved organic matter (C-DOM) also absorb in the blue-green part of the spectrum, and so absorption-based algorithms are likely to be influenced by the presence or absence of C-DOM. In extreme cases, algal-pigment signature may be drowned when such optically-active substances are present in large quantities (Case 2 waters). Conversely, absorption by C-DOM is negligible in the red part of the spectrum, and so the fluorescence algorithm is not likely to be influenced directly by C-DOM absorption. One may, however, anticipate some second-order, indirect effects, in the sense that C-DOM absorption in the blue-green part of the spectrum would diminish the amount of light absorbed by phytoplankton, and hence the amount of fluorescence per unit chlorophyll-*a* concentration (Fischer and Kronfeld, 1990). However, the fluorescence signal, when present, is uniquely attributable to chlorophyll-*a* so that it is unlikely to be confused with anything else.

- Penetration depth is typically much greater in the blue-green part of the spectrum than in the red, so that vertical structure in the water column is more likely to influence blue-green algorithms than fluorescence algorithms. (Gordon and McCluney (1975), defined "penetration depth" as that depth from within which 90% of the water-leaving radiance originates. The penetration depth in the

Table 2. *Summary of technical differences between absorption-based and fluorescence-based signals of chlorophyll-a.*

Absorption-based signal	**Fluorescence-based signal**
Non-linear function of chl-*a*	Often linear function of chl-*a*
Algorithm sensitivity greatest at low chl-*a* concentrations	Algorithm most effective at high chl-*a* concentrations
Algorithm vulnerable to C-DOM absorption	Algorithm little influenced by C-DOM absorption
"Penetration depth" high in the blue-green part of the spectrum	"Penetration depth" low in the red part of the spectrum
Atmospheric correction very critical	Atmospheric correction less critical
Potentially, information on C-DOM and suspended sediments retrieved as a by-product	Distinct signal, unconnected to other substances of interest

blue-green part of the spectrum is typically about five times greater than that in the red.) In other words, one anticipates that blue-green signals carry more information on vertical structure than fluorescence signals from the red part of the spectrum.

- Atmospheric-correction algorithms usually depend on near-infrared wavelengths to determine the spectral form of aerosol attenuation, which is then extrapolated to the visible. The errors associated with this extrapolation are likely to be greater in the blue-green part of the spectrum than in the red, and so absorption-based algorithms are liable to be more vulnerable to errors in atmospheric correction than fluorescence algorithms. Furthermore, the difference technique used in fluorescence detection uses wavelengths that are very close to each other; a consequence of this would be that the fluorescence technique is not likely to be very sensitive to spectral errors in atmospheric correction.

- Since substances such as C-DOM and suspended sediments also influence water-leaving radiances in the blue-green part of the spectrum, the potential exists, in principle, for developing advanced algorithms applicable to this part of the spectrum that would yield information on these substances. Such possibilities do not exist with a fluorescence algorithm.

In addition to these technical factors that contribute to differences between absorption-based and fluorescence-based signals of phytoplankton, physiological factors can also influence the fluorescence signal. This is examined in more detail in the next section.

3.3.2 Physiological differences between the two signals

Phytoplankton absorption coefficient, and its influence on water-leaving radiance, are determined purely by the physical and chemical characteristics of the phytoplankton population in the water, such as the pigment complement of the phytoplankton population (including changing ratios of various accessory pigments to chlorophyll-*a*), cell size and shape, and the organization of the absorbing pigments within the cell (*i.e.* pigment packaging effect). Since fluorescence depends on absorbed energy, one may argue that all these same characteristics of phytoplankton influence phytoplankton fluorescence as well. Furthermore, fluorescence also depends on the physiology of the phytoplankton cells.

For example, only the pigments associated with photosystem II of the phytoplankton cells contribute to chlorophyll-*a* fluorescence at ambient temperatures, whereas all pigments absorb. This means that some pigments that have a purely photoprotective role do not contribute to fluorescence. Furthermore, in some types of phytoplankton such as cyanophytes, most of the chlorophyll-*a* is typically associated with photosystem I rather than with photosystem II, and therefore will not fluoresce at ambient temperatures (Prézelin and Boczar, 1986; Johnsen and Sakshaug, 1996). Photodamage to photosystem II may also reduce fluorescence yield (Demmig-Adams and Adams, 1992).

In addition to the fact that light absorbed by photosystem I does not contribute to fluorescence at ambient temperatures, it is also well recognized that light absorbed by the so-called photoprotective pigments does not reach the photosystem, and therefore cannot contribute to fluorescence. Typically, photoprotective pigments are more important in the surface layers of the oceans than below, and if there is an increase in the amount of photoprotective pigments, there can be an increase in phytoplankton absorption in the blue-green part of the spectrum, with no corresponding increase in fluorescence.

One has to bear in mind that fluorescence is only one of three possible pathways that an absorbed photon may follow: A photon, once absorbed, may participate in photosynthesis, and contribute to stored chemical energy, or the energy in the photon may be dissipated as heat or as fluorescence. The quantum yields of these processes are not fixed (Kiefer and Reynolds, 1992; Babin *et al.*, 1996). In fact, the quantum yield of fluorescence is known to undergo diel variations (Loftus and Seliger, 1975; Abbott *et al.*, 1982). Nutrient limitation may also influence fluorescence yield indirectly (Loftus and Seliger, 1975; Maerker and Szekielda, 1976; Greene *et al.*, 1992). Even though the fluorescence signal is admittedly variable, and its interpretation complex, the potential exists that changes in fluorescence yield per unit pigment concentration and per unit absorbed energy, are inversely related to photosynthetic rate parameters, as demonstrated by Topliss and Platt (1986). Thus, if the absorption-based and fluorescence-based signals that are detectable by remote sensing are treated as independent pieces of information, one may be able to obtain valuable information on primary production rates in the ocean at synoptic scales. Nevertheless, a demonstration of such an application from satellites has yet to be made.

In summary, even though the fluorescence signal is difficult to interpret and to quantify in terms of chlorophyll concentration, one must bear in mind that this may be the only usable signal from phytoplankton in many Case 2 coastal waters, and we have to learn to make the best use of it. This is an area of active research (Letelier and Abbott, 1996). Fluorescence products will have to be treated as research products when they become available initially, as opposed to blue-green algorithms which are now being treated as operational products.

3.3.3 Consequences for data merging

The performances of the two techniques differ from each other, and there are expectations that they will complement each other in the sense that the performance of the absorption-based algorithm may be at its best when that of the fluorescence algorithm is at its worst, and *vice versa*. Furthermore, when the two techniques can be used in combination with each other, it may be possible to extract some additional, vital information on the photosynthetic capabilities of the phytoplankton population, which in turn could be used in primary production models. Thus, when discussing the complementarity of satellite ocean-colour missions, it is important that satellites with fluorescence capabilities, and those without, not be treated as equivalent. Furthermore, when discussing merging of ocean-colour data, chlorophyll-*a* concentrations determined using phytoplankton absorption and phytoplankton fluorescence data should not be merged as if they were equivalent: the precision and accuracy of these retrieved quantities are not expected to be the same, nor are the interpretations of the observations likely to be the same.

This discussion of the differences between techniques for retrieval of chlorophyll-*a* concentration and those for retrieval of chlorophyll-*a* fluorescence is only meant to illustrate that different ocean-colour satellites are being designed with differing technical capabilities. In addition to these efforts to monitor chlorophyll-*a* fluorescence, there are also attempts underway to use hyperspectral ocean-colour data (see Section 3.4.2 for more details) to draw out more information on phytoplankton, *e.g.*, on the presence of unusual (or harmful) algal blooms, though admittedly, much of this is still in the research and development stage. Thus, there is an understanding in the ocean-colour community that the full potential of ocean-colour technology has not yet been realized, and that further investigation and research are in order. A consequence is that while the more tried-and-tested applications of ocean-colour data move into the operational stage, other, proof-of-concept applications are being developed and tested simultaneously. The sensors designed for the latter type of applications are typically more advanced, and it is expected that the rewards from the advanced technology would be two-fold: first, an increase in the accuracy of the retrieved standard products (such as chlorophyll-*a* concentration), and second, the availability of additional products such as phytoplankton fluorescence. It is therefore important that all ocean-colour satellites not be treated as being identical to each other. Instead, when discussing the complementarity of satellites, we should also take into consideration whether the specific capabilities of a particular satellite match those of other satellites, and whether the products from the satellites under consideration can really be treated as being similar or identical to each other.

3.4 New Technologies in Ocean Colour

The new and emerging applications of ocean-colour data go hand in hand with new technologies in acquisition of ocean-colour data. These include geostationary and hyperspectral imagers.

3.4.1. Geostationary ocean-colour imagers

NASA and NOAA are currently (March, 1999) evaluating the possibility of flying an ocean-colour imager (Special Events Imager or SEI) in geostationary orbit on the Geostationary Operational Environmental Satellite (GOES-N), tentatively scheduled for launch in 2002. The mission concept includes ten to twelve visible-to-near-infrared bands, 0.3-km pixel resolution and a coverage region of 300 x 300 km. The instrument would provide SeaWiFS quality observations for a single study area with an image frequency of approximately 30 minutes. The principal applications are to:

- determine the effects of storms and tidal mixing on phytoplankton populations,
- monitor biotic and abiotic material in river plumes and tidal fronts,
- track hazardous materials (*e.g.* oil spills and noxious algal blooms).

This type of instrument is designed for very specialized purposes and would not provide routine global coverage as is possible from polar-orbiting, sun-synchronous satellites. However, a single imager on a geostationary satellite would provide multiple views of many locations during a single day, and multiple (*e.g.* three) sensors would be able to routinely observe coastal waters globally between about 60°S and 60°N.

3.4.2 Hyperspectral imagers

As noted earlier (Sections 3.2 and 3.3), some of the emerging applications of ocean-colour data require hyperspectral imagers. The U.S. Navy's NEMO is a hyperspectral remote sensing satellite for military, commercial and other uses. NEMO's launch is scheduled for the 2000-2001 timeframe. The imager will have a footprint of 30-60 m and make spectral measurements from 400-2500 nm at 10-nm resolution. Only a limited number of 200 x 50 km study sites (*ca.* 50) will be imaged during a single operational mode, although the location of the sites can be flexible. The instrument can be pointed, so that revisit time for a priority site can be as frequent as every 2.5 days. The data policy is not yet known. The imagery is of particular interest to coastal scientists and managers, including those interested in imagery of estuaries, bays, and inland waters. Other details can be found on the website: http://nemo.nrl.navy.mil/public/concept.html.

The Australian ARIES project aims to launch a high-spatial resolution, hyper-spectral sensor into low earth orbit in the year 2000. The satellite will be launched into a sun-synchronous polar orbit at an altitude of 500 km. The sensor is designed for both environmental and mineral applications, and will have 32 contiguous bands in the VIS/NIR (400 to 1100 nm), and 32 contiguous bands in the SWIR (2000 to 2500 nm), plus a panchromatic band. Spatial resolution of the spectrometer will be 30 m at nadir, with 10-m resolution panchromatic, and a ground swath of 15 km. The sensor will be able to look up to 30 degrees off vertical (along swath), providing a revisit time of seven days. Signal-to-noise ratio (SNR) specification is greater than 600:1 at 600 nm, for 30% albedo, 45° latitude with a solar angle of 60°. Further details of the mission and sensor specification can be found at the website: http://www.cossa.csiro.au/ARIES.

3.5 Meeting the Requirements

Requirements are well established for global ocean-colour measurements of the open ocean, and will be met for the 2000-2005 timeframe by satellites scheduled for launch in the near future (see Chapter 4). In contrast, ocean-colour measurements in coastal waters are far more complicated than in the open sea, and mission scenarios to meet all of the coastal requirements globally have not yet been developed. However, some of the ocean-colour satellite sensors scheduled for launch prior to 2005 offer exciting opportunities for development and testing of coastal products and applications. Of these sensors, MERIS provides a focus for coastal product development, because of the combination of high spectral resolution and 0.3-km spatial resolution. Case 2 yellow substances, chlorophyll and suspended sediment are specified as standard at-launch MERIS products.

Proof-of-concept missions may provide some new options for future coastal imaging after 2005. The potential exists to develop a range of new coastal products and applications exploiting the high spatial/temporal and/or spectral resolution of proposed new sensors such as ARIES, NEMO and SEI. Provided these products can be distributed in a timely and cost-effective manner, they have the potential to revolutionize coastal environmental management. One can envision future operational scenarios involving a combination of polar orbiting (possibly with pointing capability) and geostationary satellites that might meet many of the coastal requirements at a reasonable cost (assuming cooperation and coordination among the space agencies).

Chapter 4

Assessment of Existing and Planned Sensors up to Approximately the Year 2005

4.1 Assessment of Sensors for Minimum Requirements

We consider first the spectral band characteristics of existing and proposed broad-swath ocean-colour sensors against the spectral band set proposed in IOCCG Report No.1 (1998) in the discussion of the minimum requirements for an operational ocean-colour sensor. All the sensors listed in Table 3 include the minimum visible band set proposed in IOCCG Report No. 1 (440, 490, 560 nm), and many include the additional (optional) band at 412 nm. Note however that the Ocean Colour Imager (OCI) and the Ocean Scanning Multi-spectral Imager (OSMI), as currently specified, do not include the specified minimum two NIR bands for atmospheric aerosol correction (OSMI is an imaging spectrometer with selectable bands, and it may be possible to change the base band set).

The remaining sensors all meet the minimum spectral band requirements. However, Table 3 shows that there is considerable variation among sensors in both the exact centre wavelength and bandpass in each nominal band. This variation reflects differences in sensor design, desired SNR, and avoidance of atmospheric absorption regions.

4.2 Global Coverage

Assuming successful launches, as many as eleven ocean-colour satellites may be operating by the year 2002. Of these eleven, only SeaWiFS, MODIS-AM, MODIS-PM, MERIS, POLDER-2 and GLI meet all five criteria for scientific open-ocean missions given in Chapter 3. OCM and OSMI are proof-of-concept global missions; OCI will cover only subtropical latitudes, and SEI and NEMO are very different concepts in ocean-colour imaging for coastal waters.

Figure 2 illustrates hypothetical global coverage provided by six post-CZCS global ocean-colour sensors flown or planned by the international community (in order of launch, OCTS, SeaWiFS, MODIS-AM, MERIS, GLI, and MODIS-PM). POLDER was not included because it shared the same platform as OCTS and it will also share the same platform as GLI. It should also be noted that in case the launch sequence of sensors is altered, the coverage pattern associated with each sensor in Figure 2 will change. Results summarized by Figure 2 show that three satellites are required to produce 60% ocean coverage within three to five days, given contamination by sun glint and blocking by clouds. This three-satellite requirement can be met with a core of MODIS-AM, MERIS, and GLI for the period 1999-2002, with SeaWiFS as a backup fourth in the early part of this period and MODIS-PM at the end of the period, extending to the year 2005. If POLDER replaced OCTS and GLI in Figure 2, ocean coverage would be somewhat increased, owing to the larger swath of the instrument and its capability to handle sun-glint. Since one in five satellites does not achieve its lifetime-design requirements, and since satellite missions are often delayed, these backup satellites will probably be necessary to achieve 60% coverage through the year 2005.

The five satellites differ significantly in capability, although all meet the minimum requirements for the open ocean as previously defined (IOCCG, 1998). MODIS-AM and -PM, MERIS and GLI all have the capability to measure chlorophyll fluorescence which may provide important new information on ocean productivity. Furthermore, MERIS and GLI have other spectral bands and higher spatial resolution (0.3 km in the case of MERIS) which will provide important new capability for imaging the coastal zone. POLDER has additional capabilities for measuring: the bi-directional reflectance distribution function (BRDF) over land; aerosol properties over both land and ocean; and physical and radiative properties of clouds.

4.3 Latitudinal Coverage

The manner in which the improvements in coverage are distributed on the Earth can have important consequences. For example, losses of data near the solar declination by changing the tilt on SeaWiFS can be compensated by non-tilted satellites such as MODIS-AM, resulting in coverage improvements of more than 100% in these regions (Figure 3). Conversely, mid-latitude ocean coverage losses by MODIS-AM due to sun glint can be compensated by

Table 3. *Spectral band centre wavelengths (nm) and bandpass (Full Width at Half Maximum (FWHM), nm) of existing and proposed broad-swath ocean-colour scanners against the minimum Case 1 band requirements proposed in IOCCG Report No. 1 (1998).*

IOCCG Band No.	SeaWiFS	MODIS	OCM	MERIS	OCI	OSMI	GLI	POLDER-2
1 (865 nm)	865/20	870/15	865/40	870/20	865/40	865/40	865/20	865/40
2 (750 nm)	765/20	748/10	765/40	779/14			749/10	763/10
3 (710 nm)				709/9			710/10	
4 (560 nm)	555/20	551/10	555/20	560/10	555/20	555/20	565/10	565/20
5 (490 nm)	490/20	488/10	490/20	490/10	490/20	490/20	490/10	490/20
6 (440 nm)	443/20	443/10	443/20	442.5/10	443/20	443/20	443/10	443/20
7 (410 nm)	412/20	412/10	412/20	412.5/10			412/10	

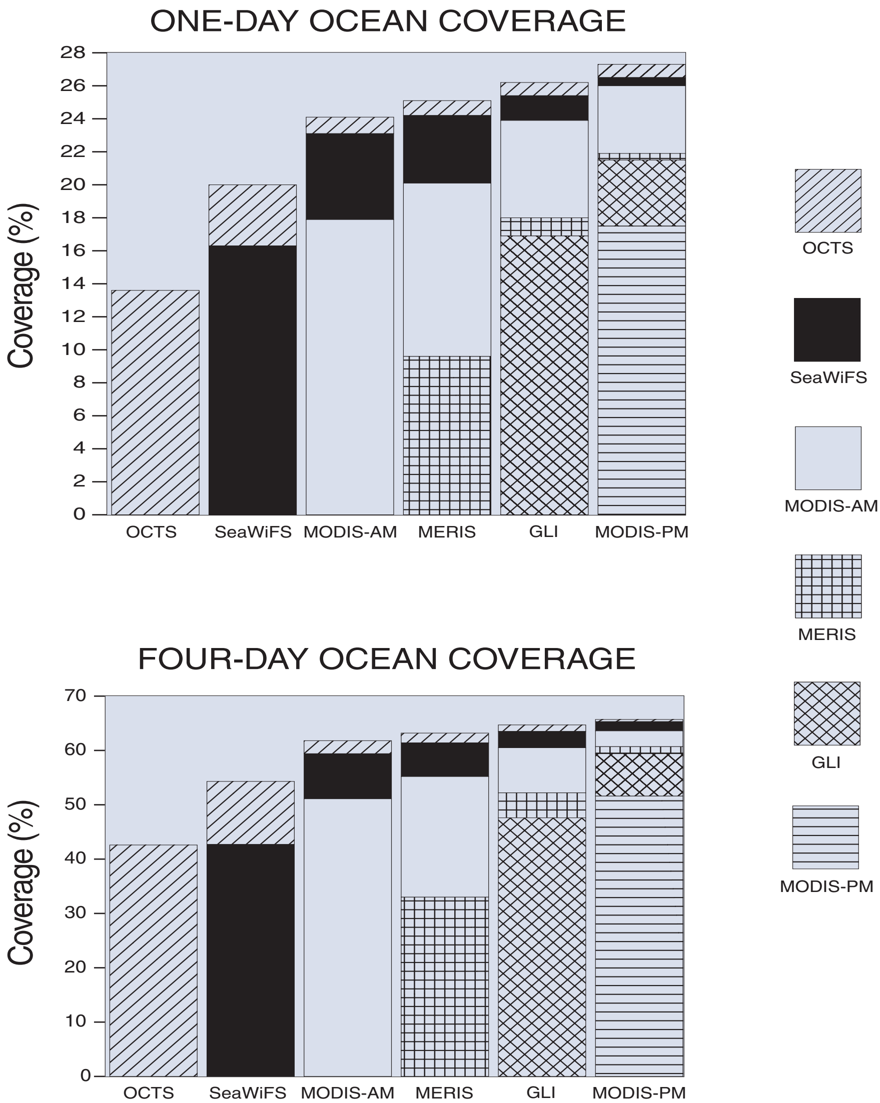

Figure 2. *Hypothetical one-day and four-day estimates of ocean coverage (percent) using six global ocean-colour sensors flown or planned in the next half-decade. Actual coverage patterns will depend upon launch sequence and other details. OCTS is no longer functional, but is included here to show general combined coverages by multiple satellites. Coverage is computed after removal of areas contaminated by excessive sun glint (see Figure 1), and by cloud cover. Clouds are allowed to change on a daily basis only. Greater coverage is possible within one day if clouds are allowed to change within the day, but the increase is not expected to be large. Coverages by the individual missions are shown at the bottom, followed by combined coverage from the previous mission, and then the next previous mission, and so forth. This enables one to evaluate the effects of losing an earlier mission and to understand individual coverages.*

SeaWiFS, resulting in a coverage improvement over that by SeaWiFS alone of more than 50%. Such complementarity enables a more-equally-dispersed view over the oceans as a whole that cannot be achieved by a single satellite mission, and this extended coverage has important consequences for observation of oceanic biological processes. These examples show that swath width, equatorial crossing times and tilt capability are all important characteristics that need to be considered when evaluating global coverage options for the post-2005 timeframe.

4.4 Temporal Coverage

The diversity of orbits for the planned suite of global ocean-colour satellites in the 2000-2005 timeframe also provides a research opportunity to evaluate the importance of diurnal variability of biological processes. Particularly noteworthy is the disparity of equator-crossing times and node, which can lead to observation of the same areas at large differences in the local time of day. The two satellites that are most different with respect to equatorial crossing time are MERIS, with a 10:00h descending

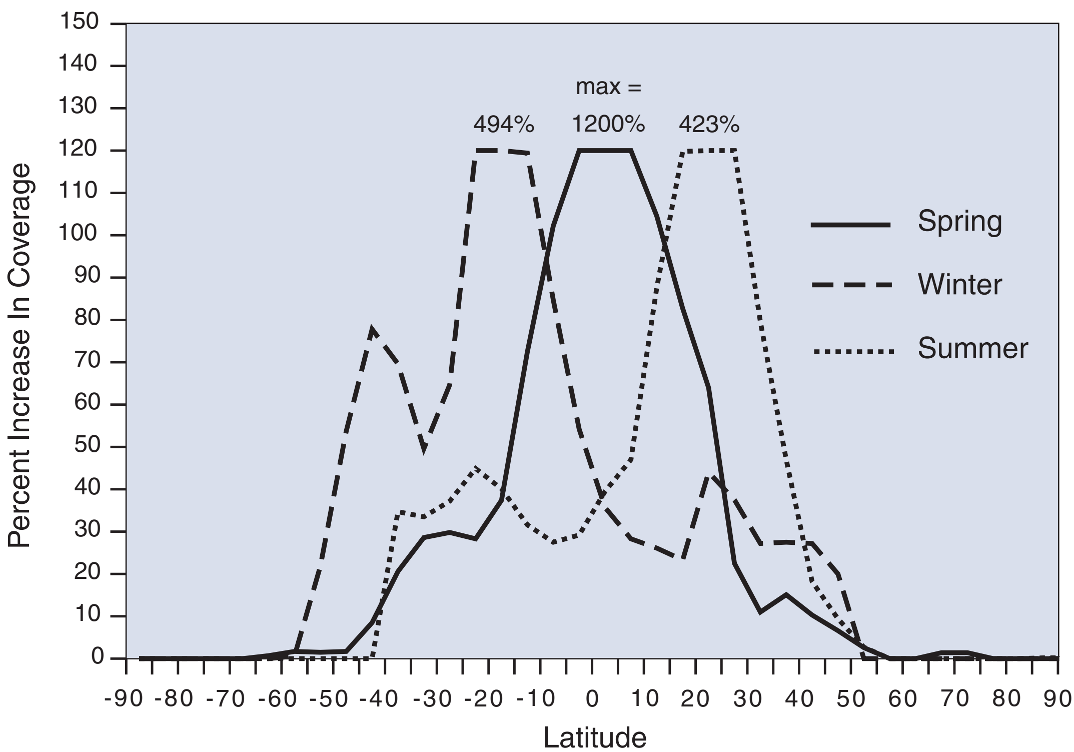

Figure 3. *Increases in coverage by latitude using combined data from SeaWiFS and MODIS-PM (from Gregg and Woodward, 1998). Individual mission coverages are not equally distributed about the global ocean surface, and the combination of data can vastly improve coverage in regions missed by one or another satellite. In this case, coverage increases are shown as percent, rather than a percent coverage of the ocean, e.g., a 10% increase means 10% greater coverage than that achieved by SeaWiFS alone.*

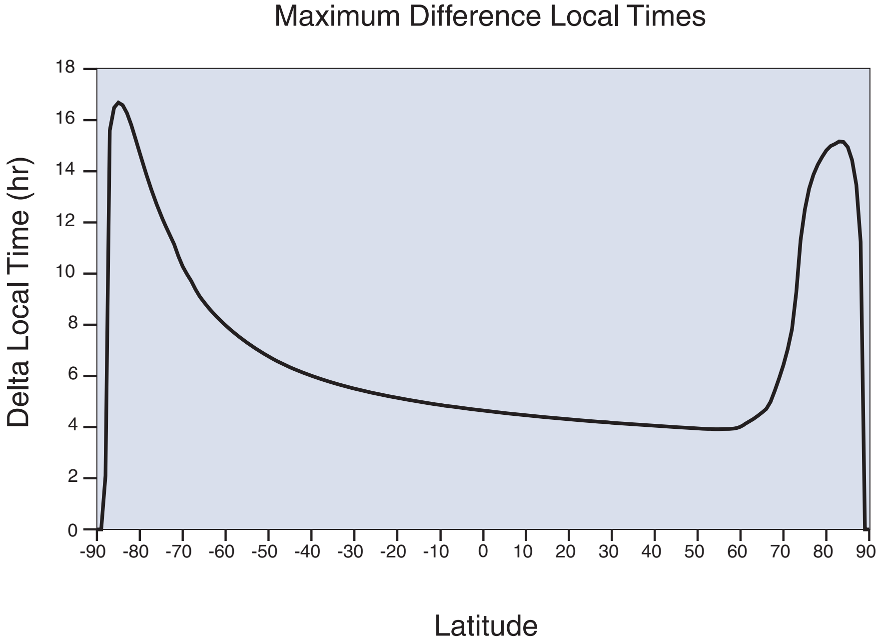

Figure 4. *Maximum time difference (local time) at co-located points by MODIS-PM and MERIS, showing the large spread in temporal observations that is possible using different satellites (from Gregg et al., 1998).*

node crossing, and MODIS-PM, with a 13:30h ascending node crossing. Differences in local observation times between these two missions are four to six hours in the low-to-mid latitudes (Figure 4), and exceeding 12 hours at the high latitudes (the latter possible only at the solstices). Such observations could lead to important new information about the temporal variability of biological processes and insights into the reliability of daily observations made with individual platforms.

Chapter 5

Data Merging and Validation

In the previous chapter, we showed that observations from multiple sensors can make a significant increase in coverage of the global ocean. A key assumption of this analysis is that the data from multiple sensors can be merged into a single global product providing continuous fields in space and time. This has not yet been accomplished with ocean-colour data and is potentially a difficult task. NASA's Sensor Inter-comparison for Marine Biological and Interdisciplinary Ocean Studies (SIMBIOS) project is a new research programme to help determine how data merger can be accomplished. The purpose of this chapter is to outline some of the major issues to consider for such a task.

5.1 Data Merging and Integration

In trying to establish an underlying basis for such an integration of ocean-colour data, several major issues have to be addressed, such as: defining the sensor-specific constraints on derived products; ensuring that processed data are available at a uniform level and in a uniform format; and developing methods for merging derived geophysical properties.

5.1.1 Constraints on ocean-colour data from satellites

Ocean-colour sensors are built to different specifications which have been established to suit the specific goals of individual missions. These specifications in turn introduce constraints on the data products, which have to be well defined. These constraints include radiometry and spectrometry.

Radiometry

The radiometric and spectral performances of the various ocean-colour data sets over a range of conditions would have to be appropriately tabulated, and evaluated over a range of conditions. Ideally, these performance levels would meet a common standard for quality. Due attention would have to be paid to a sensor's radiometric performance across its swath width, taking into account the potential need to merge data acquired under different observation geometries. For example, with respect to the issue of dealing with sun glint, threshold values would have to be established, beyond which geophysical quantities derived from sun-glint-contaminated data would not be accepted for data integration and merging. Limitations in geometrical performance such as distortions and alignment errors, as well as limitations in data quality induced by orbit manoeuvres, should be well documented.

Spectrometry

Relative spectral accuracy of the water-leaving radiance derived for various look angles and sun-zenith angles has direct repercussions on the accuracy of the derived geophysical product, and therefore is a quantity that must be known for each sensor. In addition, the method of accounting for bi-directional effects (Morel and Gentili, 1996) must also be known, together with accurate definitions of the distributed products (ocean reflectances, normalized water-leaving radiances, or directional radiances); indeed, it seems that differing definitions are presently adopted by the various agencies. The same argument holds true for the (extra-terrestrial) solar constant spectral values that are used for spectral calibration or for translating the relative results into absolute radiometric units. Knowledge of the above constraints would enable cross-referencing between geo-bio-physical variables that are derived from ocean-colour data and evaluating the potential accuracy of the derived products, which are in turn related to the spectral bands and to the algorithms that were used to derive the products. In the case of algorithms that are based on absolute rather than relative radiance, the requirements become more stringent in the sense that the absolute spectral accuracy needs to be tabulated rather than relative accuracy. In instances where significant fundamental technical and conceptual differences exist between products (see Section 3.3), it would be desirable to maintain, rather than merge, the two products, since comparisons between them might provide new insights.

5.1.2 Availability of ocean-colour data

All processed data should be available at a uniform level and in a uniform format.

Data level and quality definition

With present capabilities, the appropriate level for data to be merged and integrated is at the level of the derived geophysical variable (*i.e.*, Level-2 according to the ESA standard, or Level-3 according to the NASA standard). This would imply, for the open-ocean case, that the merging take place on the basis of data products such as chlorophyll-*a*, gelbstoff concentrations or suspended sediment distribution. It would not preclude the possibility of merging Level-3 water-leaving radiance fields as a first step towards generating other derived products (*e.g.* chlorophyll-*a*) using a common bio-optical algorithm.

Data merger can only be achieved effectively once the various constraints on sensor performance have been established, including the errors introduced into the data from the atmospheric correction procedures used in the data analyses. Furthermore, one has to define the maximum errors that may be accepted from these sources without sacrificing the desired standards of quality in the merged data. The criteria for acceptability must then be applied uniformly to all ocean-colour data products used to generate integrated and merged data products. Note that a prerequisite for this is the establishment of internationally-agreed-upon standards of quality for the derived geophysical products, which in turn will have to be established in consultation with the international user community. This in itself is a formidable undertaking, given that ocean-colour data find applications in varied and diverse fields (ranging from climate-change studies to pollution and water-quality monitoring), and given that different applications have their own individual levels of acceptable errors.

Atmospheric correction

Since the quality and reliability of radiative transfer procedures used in the data analyses play a vital role in determining the accuracy of geophysical variables retrieved and in establishing their subsequent use in integrated data, it is important to ensure that atmospheric correction procedures and the in-water radiative procedures used in the processing be well documented for all ocean-colour data sets. The operational schemes employed by the various satellite missions should be compared for a wide range of realistic situations.

Retrieval algorithms

It is also essential that comparable algorithms be used to derive the specified geophysical products at a common level. This point may necessitate the reprocessing of previously-acquired (archived) data from Level-1b (*i.e.*, top-of-the-atmosphere radiance), or reprocessing data from new sensors, if the initial procedures adopted by the individual agencies, or the historic data processing procedures, do not meet the criteria that are set for merged products. Empirical algorithms, such as those based on blue-green reflectance ratios for chlorophyll, should be established using common datasets.

Calibration

The calibration procedures and the standards against which the data have been calibrated must be known in order to facilitate the evaluation and comparison of data from sources with different methods of calibration.

5.1.3 Methods for merging higher-level data

Methods for merging ocean-colour data products need a rigorous evaluation with a view to maintaining the quality necessary for the envisaged applications. Possible techniques include splicing, averaging, weighting, "blending" and any optimized interpolation schemes. For the integration and merging of either contemporaneous large-area maps with data from different sensors and providers, or the integration of multi-temporal regional data sets, a common geographical grid has to be chosen and agreed upon. It may also be necessary to establish a hierarchy of data streams, according to which, data from sensors with the highest estimated retrieval accuracy are given the highest priority and mapped directly on to the grid of the integrated data set, and data from sensors with perceived lower accuracy are weighted accordingly, and if necessary, re-sampled, before they are mapped on to the new grid.

5.2 Validation

The geophysical data used to produce integrated data sets have to be validated at various stages. Validation of mission data products is the responsibility of individual mission teams but requires international collaboration. No single country or space agency can gather a sufficiently large dataset for comprehensive evaluation of ocean-colour retrieval. Merging data from different sensors implies that validation data sets will be shared among merger participants.

Validation activities include monitoring the following properties:

- The atmospheric conditions *in situ*, including the influence of Rayleigh scattering, aerosol, water vapour and clouds. Ideally, comparable atmospheric transfer procedures (*e.g.* taking account of multiple scattering and directionality effects) would be used to derive the geophysical variables employed in the merging. The atmospheric measurements can be utilized to test whether the radiative transfer procedures treat the existing conditions in a realistic manner, and to establish the errors introduced when certain atmospheric properties are derived in the atmospheric correction algorithms.

- The optical conditions at the sub-surface level and at the air-water interface (inherent optical properties) must also be monitored, again to verify that these conditions are estimated correctly in the algorithms, and to evaluate the errors introduced at this step of the calculations.

- The geophysical quantity that is estimated from the satellite data must also be measured *in situ* to estimate the final errors in the data product. Note that such comparisons between satellite and *in situ* estimates should take into account the consequences of scale: typically *in situ* measurements of geophysical properties are made at scales that are much smaller than the scales that are valid for the satellite estimates.

5.3 Integration

Ideally, the integration of the validated geophysical data should be "anchored" on so-called sea-truth points, which are established as a part of continuous *in situ* measurement and validation programmes. The use of moored buoys or platforms, distributed on a global scale, could form the basis for a network of sea-truth points. Linked to the sea-truth reference points, regional databases of water constituents such as chlorophyll-*a* are being established. The values derived from remotely-sensed ocean-colour data can be hinged to these data bases.

Chapter 6

Steps Toward Developing a Strategy to Coordinate Ocean-Colour Measurements from Space in the Post-2005 Timeframe

6.1 Introduction

Two decades ago ocean-colour remote sensing from space was initiated by CZCS on NASA's Nimbus-7, as a proof-of concept mission for measuring chlorophyll concentration in the ocean. During the first half of the 1980's, the data from CZCS were analysed and validated using sea-based measurements. Through these scientific activities, retrieval algorithms were improved, and new specifications for the follow-on ocean-colour instruments were established. Once the CZCS data were distributed widely beginning in 1988 (approximately ten years after launch), oceanographers and others saw many possibilities for using the imagery from follow-on missions to study coastal and open-ocean processes and to support commercial and government operations. There is strong support among biological oceanographers for continuous satellite ocean-colour observations into the foreseeable future. In fact, it is difficult for many to conceive future large-scale oceanographic research programmes without a continuous source of satellite ocean-colour data. This is particularly true for the IGBP global change research programmes, as well as for the observational programme of the Global Ocean Observing System (GOOS).

In the mid 1980's, space agencies began new initiatives to document global changes, through close international cooperation. However, scientists had to wait almost ten more years from the final CZCS image until new imagery became available following the launch of MOS-1 and OCTS in 1996. We are now on the verge of a new research phase in global ocean biological processes using data from the MOS, OCTS and SeaWiFS sensors.

Following SeaWiFS and OCTS, a new era of comprehensive observing instruments will begin, including MODIS-AM and MODIS-PM (funded by NASA), MERIS (funded by ESA) and GLI (funded by NASDA) and POLDER-2 (funded by CNES). These instruments will cover the whole Earth with multiple bands in the visible and near-infrared regions and are designed to measure substances on the land and in the ocean and atmosphere.

Multiple mission satellites represent both a benefit and a problem for ocean-colour scientists. The IOCCG recognizes cost-related and other benefits of multipurpose satellites. Strong support throughout the earth-science community is one of the necessary conditions for space agencies to continue expensive remote-sensing missions. On the other hand, multiple purpose missions make a multi-satellite coordination problem even more difficult, as each disciplinary group (land, ocean, atmosphere) has different requirements. Ocean-colour measurements may not be the principal determinant of technical requirements, including band selections and equatorial crossing times. A viable strategy for coordinating ocean-colour missions in the post-2005 timeframe has to consider the special coordination problems of multiple purpose satellites.

6.2 Tentative Plans for Future (Post 2005) Ocean-Colour Sensors

6.2.1 NASA

NASA's plans for ocean-colour measurements beyond *ca*. 2005 are evolving, although no firm programme is in place. NASA is committed to the U.S. Government's National Polar-Orbiting Operational Environmental Satellite System (NPOESS) - an operational mission as a follow-on to NOAA's Television and Infrared Observation Satellite (TIROS) series of polar orbiting satellites and the Department of Defense's meteorological satellite programme (DMSP). It is anticipated that NPOESS will be operational by 2008, and current plans call for ocean-colour measurements as part of the measurement suite. Contractor teams are presently designing the ocean-colour instrument for NPOESS based on the following minimum specifications: GAC and LAC data at 2.6- and 1.3-km resolution, respectively; determine chlorophyll concentration from 0.05 to 50 mg m^{-3} with 20% measurement precision and 30% accuracy; and repeat coverage every 48 hours.

NASA recognizes that the EOS-AM and PM platforms will not have a sufficiently long lifetime to meet the scientific objectives of the Earth Observing System (EOS) programme. NASA is thus presently planning for missions to collect Earth remote-sensing data beyond EOS-PM, and is also trying to influence the type and quality of instruments that will fly on NPOESS, with the hope that NPOESS operational sensors will also meet some of NASA's scientific requirements. One of the proposals under consideration for the *ca*. 2004 timeframe is the Advanced Global Imager (AGI). Like MODIS, AGI is a multiple purpose sensor designed for atmosphere, land and ocean scientific measurements related to EOS programme goals. The concept under evaluation includes seven ocean-colour bands centred at 412, 443, 490, 555, 645, 748 and 854 nm, and thus meets the minimum requirements for spectral bands for a global, open-ocean sensor. AGI is to be flown in a polar, sun-synchronous orbit with a morning equatorial crossing time and with no tilt capability. Although AGI is proposed as a scientific instrument, it could also be the prototype for NPOESS's operational imager.

6.2.2 NASDA

NASDA has plans for a Super-GLI (S-GLI) sensor on board the ADEOS-3 satellite, which is scheduled for launch some time in 2004. The instrument concept is similar to the GLI sensor onboard ADEOS-2;

however, the number of channels and the size of the instrument will be reduced. The instrument will be composed of three independent parts; an Ocean Colour Imager (OCI), an Atmospheric and Land Imager (ALI), and an Infrared Imager (IRI). Only the OCI component will have tilt capability. Present plans for the OCI instrument include 10 wavebands; 412, 443, 490, 520, 565, 625, 680, 710, 749 and 865 nm, with a spatial resolution of around 1 km. These specifications will meet the requirements for global observation of open-ocean, Case 1 waters, as well as Case 2 waters.

NASDA is also considering plans for a high-resolution coastal sensor. This sensor would be specifically for monitoring Asian coastal waters, and the resolution would be around 100 m. Details of this sensor are not yet specified; it may be launched as a Mission Demonstration Satellite (MDS).

6.2.3 ESA

Currently, the European Space Agency is completing the development of the MERIS Ground Segment as well as the algorithms for interpretation of MERIS observations. Dedicated studies are ongoing to establish a validation plan for MERIS data products. After the launch of the Environmental Research Satellite (ENVISAT) in early 2000 with MERIS onboard, the Agency's strategy for Earth Observation in the next decade will focus on the "Living Planet Programme". This programme was endorsed by the ESA council in March 1998 and will cover the whole spectrum of user interests, ranging from scientific research through to applications. The research-driven Earth Explorer missions will be paralleled by the applications-driven Earth Watch Missions, designed to focus on specific earth-observation applications and service provision. Currently, ESA has no firm plans for a successor to the MERIS mission, although, in both the Earth Explorer and the Earth Watch programmes the member countries of ESA will have the opportunity to pursue the development of a future ocean-colour observing system.

6.2.4 CNES

Following the development of POLDER on ADEOS-1 and ADEOS-2 and the participation in the MERIS project through the contribution to the ENVISAT programme, CNES currently has no firm plans for ocean-colour sensors beyond 2005. Tentative ideas in the research and development context involve designing a multiple purpose mission as a follow-on to both the POLDER and Vegetation missions. The concept would be based on a large swath instrument with increased capabilities in terms of spatial, spectral and angular resolution. Although not well defined at present, this mission would likely address the field of global, open-ocean monitoring.

6.3 Strategy for the Post-2005 Timeframe

The purpose of this section is to outline some of the important considerations for coordinating future ocean-colour missions. The underlying concept behind the need for such a strategy is that multiple, well-coordinated ocean-colour missions are required to meet user requirements for global temporal and spatial coverage of Case 1 and Case 2 waters. Multiple sensors with complementary technical specifications (including orbits) and with mission teams that coordinate calibration, validation, product generation and data delivery will provide international users with far more valuable data per unit cost than will uncoordinated missions. True complementarity requires cooperation among the space agencies at the mission planning stage. However, the ultimate responsibility for coordinating future missions rests with the space agencies, not with the IOCCG. The IOCCG is willing to assist the agencies but lacks the mandate from them, as well as the funds and technical resources, to put together a detailed plan for the future. The IOCCG is willing to be more active in the planning process, but its present role is limited to providing advice (*e.g.* in the form of this and other reports) and as agency plans emerge, to provide an assessment of the missions (as was done for the pre-2005 timeframe in Chapter 4). The IOCCG will revisit this important topic periodically as space agency plans develop and is willing to become involved in a higher level of coordination activity.

The goals for post-2005 ocean-colour measurements from space are to provide, in a cost-effective way, continuity measurements on a regional and global scale and improved data sets in terms of geometrical, spectral and temporal performance. Such goals will ensure an increased accuracy in the derivation of geophysical quantities in both the open oceans and the coastal zones, additional products to improve the understanding of the functioning of aquatic ecosystems in the coastal zone, the capability of frequent and accurate water quality assessments, and the observation and quantitative analysis of special (and harmful) algal blooms.

To achieve these goals, and elaborating on the present report, a strategic plan for satellite ocean-colour observations must be developed that meets the requirements (scientific and others) of the user community while taking into account planned satellite programmes and the particular objectives of individual countries and space agencies. Further, the strategic plan should ensure consistent data processing, easy data access, and include coordinated, complementary, and comprehensive calibration and evaluation programmes. Observational requirements and their respective justifications should be addressed in terms of (1) number of ocean-colour observing systems required at a given time; (2) phasing of these systems in terms of temporal and spatial performance with respect to one another; and (3) complementarity of their performances in the context of their specific applications and measurement goals. To ensure the proper phasing and complementarity of future ocean-colour observing systems, the following performances have to be given due consideration when establishing the requirements for different sensors:

- *Temporal performance*, including launch date, orbit inclination and path (descending or ascending equatorial crossing time).

- *Radiometric performance*, including NEΔL, Bidirectional Reflectance Distribution Function (BRDF) capability, radiometric calibration standard, dynamic range and quantisation.

- *Spectral performance*, including number, position and width of spectral bands, spectral sampling width and inter-band calibration.

- *Geometric performance*, including spatial (pixel) resolution, swath width symmetry of observation (*e.g.* off-nadir swath or tilt), geolocation and directional observation capability.

Users will also want to merge data from more than one sensor to improve global coverage and for other considerations. Thus data merging and product generation from multiple sensors should also be part of the strategy, possibly building on lessons learned from NASA's SIMBIOS programme. To be effective, a strategy needs to be designed and agreed upon by the satellite/sensor providers soon, ideally by the end of 1999. Now is the time to begin detailed planning!

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List of Acronyms and Abbreviations

ADEOS	Advanced Earth Observing Satellite
AGI	Advanced Global Imager
ALI	Atmospheric and Land Imager
ARIES	Australian Resource Information and Environmental Satellite
AVHRR	Advanced Very High Resolution Radiometer
AVIRIS	Airborne Visible Infrared Imaging Spectrometer
BRDF	Bidirectional Reflectance Distribution Function
C-DOM	Coloured Dissolved Organic Matter
CNES	Centre National d'Etudes Spatiales
CZCS	Coastal Zone Color Scanner
DMSP	Defense Meteorological Satellite Program
ENVISAT	Environmental Research Satellite
EOS	Earth Observing System
ESA	European Space Agency
FWHM	Full Width at Half Maximum
GAC	Global Area Coverage
GLI	Global Imager
GLOBEC	Global Ocean Ecosystems Dynamics
GODAE	Global Ocean Data Assimilation Experiment
GOES	Geostationary Operational Environmental Satellite
GOOS	Global Ocean Observing System
HAB	Harmful Algal Blooms
IGBP	Integrated Geosphere-Biosphere Programme
IGOS	Integrated Global Observing Strategy
IOCCG	International Ocean-Colour Coordinating Group
IRI	Infrared Imager
JGOFS	Joint Global Ocean Flux Study
LAC	Local Area Coverage
LOICZ	Land-Ocean Interactions in the Coastal Zone
MDS	Mission Demonstration Satellite
MERIS	Medium Resolution Imaging Spectrometer
MODIS	Moderate Resolution Imaging Spectroradiometer
MOS	Modular Optoelectric Scanner
NASA	National Aeronautics and Space Administration
NASDA	National Space Development Agency of Japan
NEΔL	Noise Equivalent Radiance
NEMO	Naval EarthMap Observer
NIR	Near Infrared
NOAA	National Oceanic and Atmospheric Administration

NPOESS	National Polar-Orbiting Operational Environmental Satellite System
OCI	Ocean Colour Imager
OCM	Ocean Colour Monitor
OCTS	Ocean Colour and Temperature Scanner
OSMI	Ocean Scanning Multispectral Imager
POLDER	Polarization and Directionality of the Earth's Reflectances
SeaWiFS	Sea-viewing Wide Field-of-view Sensor
SEI	Special Events Imager
S-GLI	Super Global Imager
SIMBIOS	Sensor Intercomparison for Marine Biological and Interdisciplinary Ocean Studies
SNR	Signal-to-Noise Ratio
SST	Sea Surface Temperature
SWIR	Short Wave Infrared
TIROS	Television and Infrared Observation Satellite
TOA	Top of the Atmosphere
VIS	Visible