ASSESSING THE REQUIREMENTS FOR SUSTAINED OCEAN COLOR RESEARCH AND OPERATIONS

Committee on Assessing Requirements for Sustained Ocean Color Research and Operations

Ocean Studies Board
Division on Earth and Life Studies

Space Studies Board
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NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

THE NATIONAL ACADEMIES PRESS
Washington, D.C.
www.nap.edu

THE NATIONAL ACADEMIES PRESS 500 Fifth Street, N.W. Washington, DC 20001

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This study was supported by the National Aeronautics and Space Administration under grant number NNX09AP57G, the National Oceanic and Atmospheric Administration under contract number DG133R08CQ0062, the National Science Foundation under grant number OCE-0948911, and the Office of Naval Research under contract number N00014-05-G-0288. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the views of the organizations or agencies that provided support for the project.

International Standard Book Number-13: 978-0-309-21044-7
International Standard Book Number-10: 0-309-21044-5

Additional copies of this report are available from the National Academies Press, 500 Fifth Street, N.W., Lockbox 285, Washington, D.C. 20055; (800) 624-6242 or (202) 334-3313 (in the Washington metropolitan area); Internet, http://www.nap.edu.

Printed in the United States of America

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Preface

Ocean biology and biogeochemistry entered a new era with the launch of the National Aeronautics and Space Administration's (NASA) Coastal Zone Color Scanner (CZCS) in 1978. For the first time, maps of phytoplankton biomass (chlorophyll)—a key measurement of marine ecosystems—could be produced from space observations with the potential for daily to interannual observations at ocean basin scales. Led by scientists based at NASA-Goddard Space Flight Center and supported by academic partners at the University of Miami and around the world, the capability to process and distribute the data developed rapidly. As a result, the numbers of applications and users also grew quickly. By the time the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) launched in 1997, regional to global maps of phytoplankton chlorophyll and other products derived from satellite measurements of water-leaving radiance (ocean color) were accessible to users all over the world and had become an essential measurement for the study and analysis of ocean biogeochemistry and ocean ecosystems.

Moderate Resolution Imaging Spectroradiometer (MODIS)-Terra launched in 1999 and MODIS-Aqua launched in 2002; the latter was a follow-on to SeaWiFS. Both had nominal ocean color capabilities, although processing Terra data for quantitative ocean color measurements proved to be an almost insurmountable challenge with only modest recent success. The increase in the number of international users and the increase in applications, however, did not lead to a clear path forward to sustain a quantitative time-series of satellite ocean color observations by U.S. sensors beyond MODIS. International partners, such as the Japanese and European Space Agency (ESA), also launched sensors, but some were short-lived, others were not suitable for global observations, and others had initial challenges to support data distribution for the international user community. In the United States, the Visible Infrared Imager Radiometer Suite (VIIRS) instrument for the National Polar-orbiting Operational Environmental Satellite System (NPOESS) platforms was to provide ocean color observations beyond MODIS, particularly for operational users. However, many ocean color users felt isolated from the planning for VIIRS and were unimpressed with the technical specifications and proposed mission operations. Many, if not most, users did not believe VIIRS could sustain the SeaWiFS/MODIS-Aqua time-series for quantitative observations. Meanwhile, SeaWiFS, both MODIS instruments, and the European Space Agency's Medium-Resolution Imaging Spectrometer (MERIS) instrument were beyond their design lifetime. This was the environment during which the committee began its task in 2010 to assess the "continuity of satellite ocean color data and associated climate research products . . . at significant risk for the U.S. ocean color community."

The committee met with experts in and out of government and hosted a community workshop to get opinions on VIIRS and non-U.S. options for future satellite ocean color measurements for U.S. users. The committee considered sensor specifications, mission operation scenarios, calibration and validation plans (or lack thereof), data exchange policies and related issues. Our task was complicated owing to major developments in ocean color remote sensing in 2010, which included: the NPOESS program was significantly restructured to become the Joint Polar Satellite System (JPSS); a team from the National Institute of Standards and Technology (NIST) characterized the VIIRS sensor with unanticipated positive results; NASA announced the Pre-Aerosol-Clouds-Ecosystem (PACE) mission, which included an advanced ocean color instrument for launch in 2019; and SeaWiFS stopped operating. With the exception of the demise of SeaWiFS, all of these were positive developments and strongly influenced our report and its conclusions. Most recently (April 2011) Congress finally approved the U.S. government's FY11 budget, which included significant cuts to the National Oceanic and Atmospheric Administration's (NOAA's) satellite programs in comparison to the President's FY11 budget submission. The implication of these cuts for

VIIRS on NPOESS Preparatory Project (NPP) and JPSS-1 are not known to the committee.

Many individuals from NASA, NOAA, private industry, and academia attended the open sessions of our meetings and contributed essential information. In particular, many of these individuals helped the committee understand very technical issues as well as the complex organizational issues associated with the restructuring of NPOESS. I am also grateful to the committee members who worked so well together and were able to come to consensus on all of the important issues.

Finally, I am most grateful to the National Research Council (NRC) staff—Study Director, Claudia Mengelt; Senior Program Assistant, Jeremy Justice; Program Assistant, Emily Oliver; Senior Program Assistant, Heather Chiarello; and Ocean Studies Board Director, Susan Roberts for all of the time and effort they dedicated to the completion of this report.

Jim Yode, *Chair*
Committee on Assessing Requirements for
Sustained Ocean Color Research and Operations

Acknowledgment of Reviewers

This report was greatly enhanced by the participants of the meetings held as part of this study. The committee would first like to acknowledge the efforts of those who gave presentations at meetings: Steve Ackleson (ONR), Bob Arnone (NRL), Paula Bontempi (NASA), Emmanuel Boss (University of Maine), Tony Busalacchi (University of Maryland), Curt Davis (OSU), Paul DiGiacomo (NOAA), James Gleason (NASA), Bruce Guenther (NOAA), Carol Johnson (NIST), Henri Laur (ESA), Charles McClain (NASA), Hiroshi Murakami (JAXA), Steve Murawski (NOAA), Fred Pratt (GSF), Peter Regner (ESA), Karen St. Germaine (NOAA), Phil Taylor (NSF), Kevin Turpie (NASA), Menghua Wang (NOAA), Stan Wilson (NOAA), and Giuseppe Zibordi (Joint Research Centre, Ispra). These talks helped set the stage for fruitful discussions in the closed sessions that followed.

The committee is also grateful to a number of people who provided important discussion, submitted white papers, and helped improve the quality of this report: Paul DiGiacomo (NOAA), Carol Johnson (NIST),Charles McClain (NASA), Stan Wilson (NOAA), and Shelby Wood.

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the NRC's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that this report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their participation in their review of this report:

WILLIAM M. BALCH, Bigelow Laboratory for Ocean Sciences, Boothbay Harbor, Maine
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Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations nor did they see the final draft of the report before its release. The review of this report was overseen by **Francisco P. Chavez**, Monterey Bay Aquarium Research Institute, appointed by the Divison on Earth and Life Studies, who was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

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Summary

The ocean hosts a fundamental component of Earth's biosphere. Marine organisms play a pivotal role in the cycling of life's building blocks such as nitrogen, carbon, oxygen, silica, and sulfur. About half of the global primary production—the process by which CO_2 is taken up by plants and converted to new organic matter by photosynthesis—occurs in the ocean. Most of the primary producers in the ocean comprise microscopic plants and some bacteria; these photosynthetic organisms (phytoplankton) form the base of the ocean's food web. Scientists are exploring how future climate change and sea surface warming might impact the overall abundance of phytoplankton. A long-term change in phytoplankton biomass would have major implications for the ocean's ability to take up atmospheric CO_2 and support current rates of fish production. Therefore, sustaining a global record of the abundance of phytoplankton and their contribution to global primary productivity is required to assess the overall health of the ocean, which is currently threatened by multiple stresses such as increased temperature and ocean acidification (both due to anthropogenic CO_2 emissions), marine pollution, and overfishing.

Because the ocean covers roughly 70 percent of Earth's surface, ships alone cannot collect observations rapidly enough to provide a global synoptic view of phytoplankton abundance. Only since the launch of the first ocean color satellite (the Coastal Zone Color Scanner [CZCS] in 1978) has it been possible to obtain a global view of the ocean's phytoplankton biomass in the form of chlorophyll. These observations led to improved calculations of global ocean primary production, as well as better understanding of the processes affecting how biomass and productivity change within the ocean basins at daily to interannual time scales.

THE OCEAN COLOR TIME-SERIES IS AT RISK

Currently, the continuous ocean color data record collected by satellites since the launch of the Sea-viewing Wide Field-of-view Sensor (SeaWiFS, in 1997) and the Moderate Resolution Imaging Spectroradiometer (MODIS, on Terra in 1999 and on Aqua in 2002) is at risk. The demise of SeaWiFS in December 2010 has accentuated this risk. MODIS on Aqua is currently the only U.S. sensor in orbit that meets all requirements (see below) for sustaining the climate-quality[1] ocean color time-series and products. However, this sensor is also many years beyond its design life. Furthermore, it is no longer possible to rectify problems with the Aqua sensor degradation that were addressed through comparisons with SeaWiFS in the past few years. Therefore, it is uncertain how much longer data from U.S. sensors will be available to support climate research. Although the European Medium-Resolution Imaging Spectrometer (MERIS) meets all the requirements of a successful mission, it is also beyond its design life. Because of the many uncertainties surrounding the next U.S. satellite mission (more specifically the Visible Infrared Imager Radiometer Suite [VIIRS] sensor scheduled to launch fall 2011); data acquired through the VIIRS mission threaten to be of insufficient quality to continue the climate-quality time-series.

Even if fully successful, the VIIRS sensor's capabilities are too limited to explore the full potential of ocean color remote sensing. Thus, the U.S. research community is looking to National Aeronautics and Space Administration (NASA) to provide ocean color sensors with advanced capabilities to support new applications and for significant improvements to current research products beyond what is possible with data from SeaWiFS and MODIS or will be possible from VIIRS. However, the Pre-Aerosol-Clouds-Ecosystem (PACE)—the first of NASA's planned three missions that would advance the capabilities for basic ocean color research—is not scheduled to launch before 2019.

Without the ability to sustain high-quality ocean color measurements or to launch next generation sensors with new

[1] Climate-quality observations are a time-series of measurements of sufficient length, consistency, and continuity to assess climate variability and change (following NRC, 2004b).

capabilities, many important research and operational uses are compromised, including the capability to detect impacts of climate change on primary productivity. Therefore, it is imperative to maintain and improve the capability of satellite ocean color missions at the accuracy level required to understand changes to ocean ecosystems that potentially affect living marine resources and the ocean carbon cycle, and to meet other operational and research needs. Given the importance of maintaining the data stream, the National Oceanic and Atmospheric Administration (NOAA), NASA, the National Science Foundation (NSF), and the Office of Naval Research (ONR) asked the National Research Council to convene an ad hoc study committee to review the minimum requirements to sustain global ocean color radiance measurements for research and operational applications and to identify options to minimize the risk of a data gap (see Box S.1 for the full statement of task). Because the ability to sustain current capabilities is at risk, the report focuses on minimum requirements to sustain ocean color observations of a quality equivalent to the data collected from SeaWiFS. Meeting these requirements will mitigate the risk of a gap in the ocean color climate data record but will be insufficient to explore the full potential of ocean color research and will fall short of meeting all the needs of the ocean color research and operational community. To meet all these needs, a constellation of multiple sensor types[2] in polar and geostationary orbits will be required. Note that satellite requirements for research leading to the generation of novel products would vary depending on the question addressed and are difficult to generalize.

THE REQUIREMENTS TO OBTAIN HIGH-QUALITY GLOBAL OCEAN COLOR DATA

Satellite ocean color sensors measure radiance at different wavelengths that originate from sunlight and are backscattered from the ocean and from the atmosphere. Deriving the small ocean component from the total radiance measured by satellite sensors is a complex, multi-step process. Each step is critical and needs to be optimized to arrive at accurate and stable measurements. Using a set of algorithms (starting with removal of the contribution from the atmosphere, which is most of the signal), radiance at the top of the atmosphere is converted to water-leaving radiance (L_w) and then to desired properties such as phytoplankton abundance and primary productivity. To detect long-term climactic trends from these properties, measurements need to meet stringent accuracy requirements. Achieving this high accuracy is a challenge, and based on a review of lessons learned from the SeaWiFS/MODIS era, requires the following steps to sustain current capabilities:

1. The sensor needs to be well characterized and calibrated prior to launch.
2. Sensor characteristics, such as band-set and signal-to-noise, need to be equivalent to the combined best attributes from SeaWiFS and MODIS.
3. Post-launch vicarious calibration[3] using a Marine Optical Buoy (MOBY)-like approach with in situ measurements that meet stringent standards is required to set the gain factors of the sensor.
4. The sensor stability and the rate of degradation need to be monitored using monthly lunar looks.[4]
5. At least six months of sensor overlap are needed to transfer calibrations between space sensors and to produce continuous climate data records.
6. The mission needs to support on-going development and validation of atmospheric correction, bio-optical algorithms, and ocean color products.
7. Periodic data reprocessing is required during the mission.
8. A system needs to be in place that can archive, make freely available, and distribute rapidly and efficiently all raw,[5] meta- and processed data products to the broad national and international user community.
9. Active research programs need to accompany the mission to improve algorithms and products.
10. Documentation of all mission-related aspects needs to be accessible to the user community.

Meeting these requirements would contribute to sustaining the climate-quality global ocean color record for the open ocean. However, further enhancements to sensors and missions, such as higher spectral and spatial resolution, will be required to meet the research and operational needs for imaging coastal waters and for obtaining information about the vertical distribution of biomass or particle load. High frequency sampling (e.g., imagery every 30 minutes for a fixed ocean area), such as can be obtained from geostationary orbit, are desirable enhancements for applications such as ecosystem and fisheries management, as well as naval applications.

[2] Type 1: Polar orbiting sensors with relatively low spatial resolution (1 km) with 8 (or many more) wave bands.

Type 2: Polar orbiting sensors with medium spatial resolution (250-300 m) and more bands to provide a global synoptic view at the same time as allowing for better performance in coastal waters.

Type 3: Hyper-spectral sensors with high spatial resolution (~30m) in polar orbit.

Type 4: Hyper- or multi-spectral sensors with high spatial resolution in geostationary orbit.

[3] Vicarious calibration refers to techniques that use natural or artificial sites on the surface of Earth and models for atmospheric radiative transfer to provide post-launch absolute calibration of sensors.

[4] Monthly lunar looks refers to the spacecraft maneuver that looks at the surface of the moon once a month as a reference standard to determine how stable the sensor's detectors are. The information from the lunar looks is then used for determining temporal changes in sensor calibration.

[5] Raw data is defined as data in engineering units to which new calibration factors can be applied to generate radiance values at the top of the atmosphere.

Box S.1
Statement of Task

Continuity of satellite ocean color data and associated climate research products are presently at significant risk for the U.S. ocean color community. Temporal, radiometric, spectral, and geometric performance of future global ocean color observing systems must be considered in the context of the full range of research and operational/application user needs. This study aims to identify the ocean color data needs for a broad range of end users, develop a consensus for the minimum requirements, and outline options to meet these needs on a sustained basis.

An ad hoc committee will assess lessons learned in global ocean color remote sensing from the SeaWiFS/MODIS era to guide planning for acquisition of future global ocean color radiance data to support U.S. research and operational needs. In particular, the committee will assess the sensor and system requirements necessary to produce high-quality global ocean color climate data records that are consistent with those from SeaWiFS/MODIS. The committee will also review the operational and research objectives, such as described in the Ocean Research Priorities Plan and Implementation Strategy, for the next generation of global ocean color satellite sensors and provide guidance on how to ensure both operational and research goals of the oceanographic community are met. In particular the study will address the following:

1. Identify research and operational needs, and the associated global ocean color sensor and system high-level requirements for a sustained, systematic capability to observe ocean color radiance (OCR) from space;
2. Review the capability, to the extent possible based on available information, of current and planned national and international sensors in meeting these requirements (including but not limited to: VIIRS on NPP and subsequent JPSS spacecrafts; MERIS on ENVISAT and subsequent sensors on ESA's Sentinel-3; S-GLI on JAXA's GCOM-C; OCM-2 on ISRO's Oceansat-2; COCTS on SOA's HY-1; and MERSI on CMA's FY-3);
3. Identify and assess the observational gaps and options for filling these gaps between the current and planned sensor capabilities and timelines; define the minimum observational requirements for future ocean color sensors based on future oceanographic research and operational needs across a spectrum of scales from basin-scale synoptic to local process study, such as expected system launch dates, lifetimes, and data accessibility;
4. Identify and describe requirements for a sustained, rigorous on-board and vicarious calibration and data validation program, which incorporates a mix of measurement platforms (e.g., satellites, aircraft, and in situ platforms such as ships and buoys) using a layered approach through an assessment of needs for multiple data user communities; and
5. Identify minimum requirements for a sustained, long-term global ocean color program within the United States for the maintenance and improvement of associated ocean biological, ecological, and biogeochemical records, which ensures continuity and overlap among sensors, including plans for sustained rigorous on-orbit sensor inter-calibration and data validation; algorithm development and evaluation; data processing, re-processing, distribution, and archiving; as well as recommended funding levels for research and operational use of the data.

The review will also evaluate the minimum observational research requirements in the context of relevant missions outlined in previous NRC reports, such as the NRC "Decadal Survey" of Earth Science and Applications from Space. The committee will build on the Advance Plan developed by NASA's Ocean Biology and Biogeochemistry program and comment on future ocean color remote sensing support of oceanographic research goals that have evolved since the publication of that report. Also included in the review will be an evaluation of ongoing national and international planning efforts related to ocean color measurements from geostationary platforms.

ASSESSMENT OF CURRENT AND FUTURE SENSORS IN MEETING THESE REQUIREMENTS

As Figure S.1 indicates, all current sensors except for Ocean Colour Monitor on-board Oceansat-2 (OCM-2) are beyond their design life. The recent demise of SeaWiFS is also putting into question the future of the MODIS sensors because their recent rapid degradation resulted in a reliance on SeaWiFS data to calibrate the MODIS data. Without this calibration, it is unclear how long MODIS data can be made available at the necessary accuracy. MERIS is a high-quality mission but also beyond its design life.

Therefore, the launch of VIIRS planned for fall 2011 comes at a very critical time. Unless there is a successful transition from European Space Agency's (ESA) MERIS to ESA's Ocean Land Colour Instrument (OLCI) sensor, and data from OCLI are available immediately, the success and the continuity of the global ocean color time-series will be dependent on the success of the VIIRS mission, because OCM-2 does not collect global data.

The research community has long questioned the ability of VIIRS to deliver high-quality data because of a manufacturing error in one of its optical components. Since this issue has been raised, the sensor has been mounted onto its launch vehicle and undergone additional testing and char-

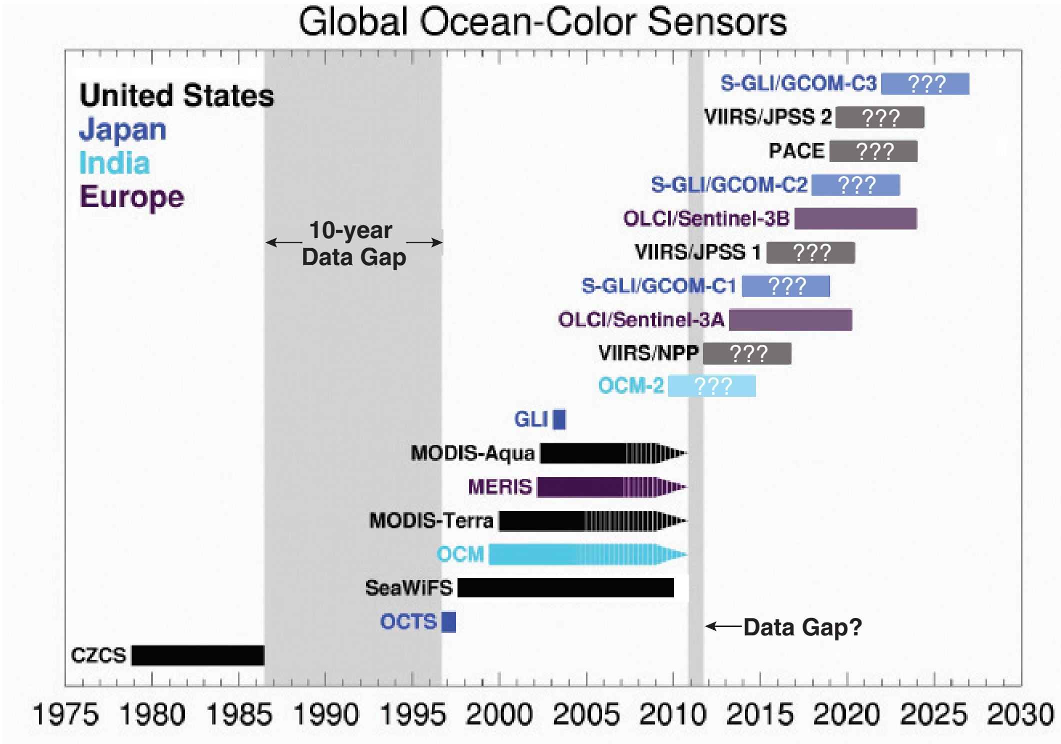


FIGURE S.1 The launch sequence of past, current, and planned ocean color sensors in polar orbit are displayed. The sensors still operational are shown with a one-sided arrow; the hatched area indicates when a sensor is beyond its design life. The gray shaded background indicates a data gap in the past and a potential data gap if MODIS sensors and MERIS cease today. The question marks are used to indicate sensors that either do not yet meet the minimum requirements or are vulnerable to changes in funding allocation. Future sensors are shown having either a five- or seven-year lifetime, according to their individual specifications. CZCS: Coastal Zone Color Scanner; OCTS: Ocean Color and Temperature Scanner; SeaWiFS: Sea-viewing Wide Field-of-view Sensor; OCM/OCM-2: Ocean Colour Monitor; MODIS-Terra/MODIS-Aqua: Moderate Resolution Imaging Spectroradiometer on Terra/Aqua, respectively; MERIS: Medium Resolution Imaging Spectrometer; GLI: Global Imager; VIIRS: Visible Infrared Imager Radiometer Suite; OLCI: Ocean Land Colour Instrument onboard Sentinel-3; PACE: Pre-Aerosol-Clouds-Ecosystem; GCOM-C: Global Change Observation Mission for Climate Research; JPSS: Joint Polar Satellite System. SOURCE: Based on data from http://www.ioccg.org/sensors_ioccg.html.

acterization. The most recent tests have resulted in a more optimistic assessment about its performance, and a software solution to overcome part of the optical hardware issue has been proposed.

However, based on the committee's assessment of the overall planning and budgeting, it is currently unlikely that this mission will provide data of sufficient quality to continue the ocean color climate data record. This conclusion reflects inadequacies in the current overall mission design and provisions to address all the key requirements of a successful ocean color mission (see above for 10 requirements). In particular, NOAA has not developed a capacity to process and reprocess the data such as is available at NASA.

Conclusion: VIIRS/NPP has the potential to continue the high-quality ocean color time-series only if NOAA takes ALL of the following actions:

1. implement spacecraft maneuvers as part of the mission, including monthly lunar looks using the Earth-viewing port to quantify sensor stability;

2. form a calibration team with the responsibility and authority to interact with those generating Level 1[6] products, as well as with the mission personnel responsible for

[6] There are five different levels of processing of satellite data:

Level 0: Raw data as measured directly from the spacecraft in engineering units (e.g., volts or digital counts).

Level 1: Level 0 data converted to radiance at the top of the atmosphere using pre-launch sensor calibration and characterization information adjusted during the life of the mission by vicarious calibration and stability monitoring.

Level 2: Data generated from Level 1 data following atmospheric correction that are in the same satellite viewing coordinates as Level 1 data.

Level 3: Products that have been mapped to a known cartographic projection or placed on a two-dimensional grid at known spatial resolution.

Level 4: Results derived from a combination of satellite data and ancillary information, such as ecosystem model output.

the sensor, to provide the analyses needed to assess trends in sensor performance and to evaluate anomalies;

3. implement a vicarious calibration process and team using a MOBY-like approach;

4. implement a process to engage experts in the field of ocean color research to revisit standard algorithms and products, including those for atmospheric correction, to ensure consistency with those of heritage instruments and for implementing improvements;

5. form a data product team to work closely with the calibration team to implement vicarious and lunar calibrations, oversee validation efforts, and provide oversight of reprocessing; and

6. provide the capability to reprocess the mission data multiple times to incorporate improvements in calibration, correct for sensor drift, generate new and improved products, and for other essential reasons.

Conclusion: If these steps are not implemented, the United States will lose its capability to sustain the current time-series of high-quality ocean color measurements from U.S. operated sensors in the near future, because the only current viable U.S. sensor in space (MODIS-Aqua) is beyond its design life.

Regardless of how well VIIRS performs, it has only a very limited number of ocean color spectral bands and thus cannot provide the data required by the research community for advanced applications. Under ideal conditions of international cooperation, data from U.S. and non-U.S. sensors planned for the future could be made readily available to meet the many needs for research and operations, but ideal conditions are difficult to negotiate for many complicated reasons. The European MERIS mission is currently providing high-quality global data, albeit with somewhat less frequent global coverage owing to its narrower swath as compared to the U.S. missions. The European Space Agency (ESA) expects MERIS will continue to operate until its follow-on sensor (OLCI) is launched on ESA's Sentinel-3 platforms in 2013. ESA, NASA and NOAA have ongoing discussions about full exchange of MERIS mission data, including raw satellite data and calibration data. The Indian space agency launched the OCM-2 sensor in 2009. OCM-2 has excellent technical specifications, but to date, data access is very limited. Furthermore, OCM-2 is not a global mission; its data collection priority focuses on the Indian Ocean. The Japanese space agency is planning an advanced ocean color sensor, Second-Generation Global Imager (S-GLI), for launch in 2014 that has high potential based on its technical specifications.

Conclusion: Under the following conditions non-U.S. sensors can be viable options in replacing or augmenting data:

1. A U.S. program is established to coordinate access to data from non-U.S. sensors, including full access to prelaunch characterization information and timely access to post-launch Level 1 or Level 0 data, and direct downlink for real-time access; and

2. This program includes sufficient personnel and financing to collect independent calibration and validation data, assess algorithms and develop new algorithms as required, produce and distribute data products required by U.S. users, support interactions among U.S. research and operational users in government, academia and the private sector, and has the capability to reprocess data from U.S. missions (e.g., MODIS, SeaWiFS) as well as the non-U.S. sensors to establish a continuous time-series of calibrated data.

The committee finds that non-U.S. sensors can be viewed as a source of data to complement and enhance U.S. missions. For example, merging calibrated data from multiple sensors, particularly if the sensors have different equatorial crossing times, can provide much more complete global coverage than is possible from a single sensor. Mean coverage from a single sensor averages about 15 percent of the global ocean per day, owing to cloud cover and limitations imposed by swath width and orbit characteristics. Daily coverage can be increased by merging data from multiple sensors, if they are in complementary orbits. Furthermore, sensors such as MERIS, OLCI, and OCM-2 have much better capabilities—including higher spatial and spectral resolution—for imaging coastal waters than current U.S. sensors or VIIRS. Routine access to the data from these non-U.S. sensors, particularly MERIS and OLCI, is essential to advance the research and operational uses of ocean color data for U.S. coastal applications. OCM-2 has potential but is not currently operated for global observations.

Finally, non-U.S. space agencies are taking some of the development risk for new approaches to ocean color data collection. For example, South Korea in 2010 became the first country to put an ocean color imager into geostationary orbit (viewing the East China Sea), and thus will help the international user community understand the potential of this approach, including the capability to view the same ocean area about every 30 minutes during daylight hours.

MINIMIZING THE RISK OF A DATA GAP

The risk of a data gap in the U.S. ocean color time-series is very real and imminent because MODIS is not likely to deliver high-quality data for much longer. Many issues remain unresolved regarding the VIIRS missions, and the next U.S. ocean color mission, NASA's Pre-Aerosol-Clouds-Ecosystem (PACE) mission, will not launch before 2019. To minimize this risk, the principal recommendation of the committee is:

Recommendation: NOAA should take all the actions outlined above to resolve remaining issues with the VIIRS/NPP. In addition, NOAA needs to fix the hardware problems on the subsequent VIIRS sensors and ensure all the above actions are incorporated into the mission planning for the subsequent VIIRS launches on JPSS-1 and JPSS-2. Taking these steps is necessary to generate a high-quality dataset, because VIIRS is the only opportunity for a U.S. ocean color mission until the launch of NASA's PACE mission, currently scheduled for launch no earlier than 2019. In addition, if MERIS ceases operation before Sentinel-3A is launched in 2013, VIIRS/NPP would be the only global ocean color sensor in polar orbit.

To develop quality ocean color products requires highly specialized skill and expertise. Currently, the NASA Ocean Biology Processing Group (OBPG) at Goddard Space Flight Center (GSFC) is internationally recognized as a leader in producing well-calibrated, high-quality ocean color data products from multiple satellite sensors. NOAA currently lacks the demonstrated capacity to readily produce high-quality ocean color products and provide the comprehensive services currently available from the OBPG, although NOAA is in the process of building its capacity. For example, although NOAA's National Climate Data Center (NCDC) plans to archive a climate-level[7] radiance data record, it is unclear how NOAA can generate the products or make them easily accessible to U.S. and foreign scientists.

Both NASA and NOAA support ocean color applications, with NASA focused primarily on research and development and NOAA focused on operational uses. Because both agencies have a strong interest in climate and climate impacts, they share a common interest in climate data records.If NOAA builds its own data processing/reprocessing group, two independent federal groups will then be developing ocean color products and climate data records. While this can be justified given the distinct missions of NOAA and NASA, it can also raise problems when discrepancies appear in the data records. Moreover, the committee anticipates major challenges to generating high-quality products from the VIIRS/NPP data, which call for involving the expertise currently only available at NASA's OBPG. For these reasons, the committee concludes the following:

Conclusion: NOAA would greatly benefit from initiating and pursuing discussions with NASA for an ocean color partnership that would build on lessons learned from SeaWiFS and MODIS, in particular.[8]

[7] Climate-level means repackaged data to look like a MODIS granule and all metadata repackaged accordingly to ease the reprocessing of the Level 0 data.

[8] Consistent with the conclusions and recommendations of "Assessment of Impediments to Interagency Collaboration on Space and Earth Science Missions" (NRC, 2010).

Recommendation: To move toward a partnership, NASA and NOAA should form a working group to determine the most effective way to satisfy the requirements of each agency for ocean color products from VIIRS and to consider how to produce, archive, and distribute products of shared interest, such as climate data records, that are based on data from all ocean color missions. This group should comprise representatives from both agencies and include a broad range of stakeholders from the ocean color research and applications community.

Based on its review of previous ocean color missions, the committee concludes that a long-term national program to support ocean color remote sensing involves multiple agencies—NOAA and NASA in particular, with input from the academic research community, and continuous funding that goes beyond the lifetime of any particular satellite mission. Such a mechanism is required to ensure that:

1. continuity is achieved and maintained between U.S. and non-U.S. satellite missions;
2. lessons learned from previous missions are incorporated into the planning for future missions;
3. mission planning and implementation are timed appropriately to ensure continuity between satellite missions;
4. capability for data processing and reprocessing of U.S. and non-U.S. missions is maintained; and
5. planning for transition from research to operation occurs early for each mission and is implemented seamlessly via cooperation and interaction between government, academic, and private-sector scientists.

Recommendation: To sustain current capabilities, NOAA and NASA should identify long-term mechanisms that can:

- provide stable funding for a MOBY-like approach for vicarious calibration;
- maintain the unique ocean color expertise currently available at NASA's OBPG over the long term and make it available to all ocean color missions;
- nurture relations between NASA and NOAA scientists so that both agencies meet their needs for ocean color data in the most cost-effective manner and without needless duplication;
- establish and maintain validation programs, and maintain and distribute the data over the long term;
- provide the planning and build the will for continuity in the satellite missions over the long term; and
- sustain the viability of the scientific base by supporting research and training.

The committee envisions that such a mechanism could be a U.S. working group modeled after the International Ocean Colour Coordinating Group (IOCCG). The establishment of a working group with representation from all the interested federal agencies, from U.S. academic institutions and the private sector could provide the necessary long-range planning to meet the needs of U.S. users, provide external advice to the individual missions, interact with foreign partners, and develop consensus views on data needs and sensor requirements.

CONCLUSION

The diverse applications of, and future enhancements to, ocean color observations will require a mix of ocean color satellites in polar and geostationary orbit with advanced capabilities. Although the three missions described in NASA's Decadal Survey (Aerosol-Cloud-Ecosystem/Pre-Aerosol-Cloud-Ecosystem, Geostationary Coastal and Air Pollution Events [GEOCAPE], and Hyperspectral Infrared Imager [HyspIRI]) will potentially provide many advanced capabilities, meeting all user needs within the next decade will likely surpass the capability of a single space agency or nation.

Conclusion: U.S. scientists and operational users of satellite ocean color data will need to rely on multiple sources, including sensors operated by non-U.S. space agencies, because the United States does not have approved missions to sustain optimal ocean color radiance data for all applications.

Recommendation: NOAA's National Environmental Satellite, Data, and Information Service and NASA's Science Mission Directorate should increase efforts to quickly establish lasting, long-term data exchange policies, because U.S. users are increasingly dependent on ocean color data from non-U.S. sensors.

The IOCCG presents an effective body through which NASA and NOAA can engage with foreign space agencies and develop a long-term vision for meeting the research and operational needs for ocean color products. Through the IOCCG, space agencies can identify options for collaborations and approaches mutually beneficial to all interested parties. The group has been active in communicating user needs and is working with the Committee on Earth Observation Satellites (CEOS) to develop plans for the Ocean Colour Radiometry Virtual Constellation[9] (OCR-VC). In the long term, international partnerships will be needed to sustain the climate-quality global ocean color time-series, and at the same time, to advance ocean color capabilities and research.

[9] A virtual constellation is a set of space and ground segment capabilities operating together in a coordinated manner; in effect, a virtual system that overlaps in coverage in order to meet a combined and common set of Earth Observation requirements. The individual satellites and ground segments can belong to a single or multiple owners.

1

Introduction

The ocean is a fundamental component of Earth's biosphere. Because the ocean is so vast and difficult for humans to explore, satellite remote sensing of ocean color is currently the only way to observe and monitor the biological state of the surface ocean globally on time scales of days to decades.

The ocean covers roughly 70 percent of Earth's surface and plays a pivotal role in the cycling of life's building blocks such as nitrogen, carbon, oxygen, and sulfur. The ocean also contributes to regulating the climate system. For example, the land and ocean together removed 57 percent of all anthropogenic carbon dioxide (CO_2) emissions from 1958 to 2009,[1] with the ocean accounting for about half of this. By removing CO_2 from the atmosphere, the ocean moderates the rate of human-induced climate change. In addition, the CO_2 dissolving in the ocean produces carbonic acid, which is causing the ocean to become more acidic. Moreover, the ocean has absorbed approximately 90 percent of the increased heat associated with climate change (Lyman et al., 2010). As the ocean grows warmer and more acidic, these changes may have adverse effects on whole groups of marine organisms (NRC, 2010). Additional stressors—such as overfishing, nutrient pollution from land runoff, coastal development, and invasive species—further jeopardize the health of the ocean and the vital functions it provides (NRC, 2004a).

Monitoring the health of the ocean and its productivity is critical to understanding and managing the ocean's essential functions and living resources. Phytoplankton are microscopic organisms responsible for most of the primary production[2] in the ocean, are ubiquitous in the surface ocean, and form the base of the marine food web. Tracking changes in phytoplankton in the vast expanse of the ocean requires a perspective that can be gained only from satellite measurements (NRC, 2008a). Ocean color measurements from space have revolutionized our understanding of the ocean on every scale, from local to global and from days to decades.

Ocean color measurements reveal a wealth of ecologically important characteristics including: chlorophyll concentration (a proxy for the biomass of marine plants or phytoplankton), the rate of phytoplankton photosynthesis, sediment transport, dispersion of pollutants, and responses of oceanic biota to long-term climate changes (IOCCG, 2008). Many scientists and operational users, such as managers of coastal resources and fisheries, rely on these measurements for research, ecosystem monitoring, and resource management.

DERIVING OCEAN PROPERTIES FROM OCEAN COLOR RADIANCE

Deriving biological parameters from ocean color measurements is a multi-stage process. Ocean color radiometric sensors measure the upwelling radiance at the top of the atmosphere (L_{TOA}). As illustrated in Figure 1.1, L_{TOA} is the total radiances from three sources: water-leaving radiance (L_w) radiance reflected from the sea surface (surface-reflected radiance), and radiance scattered into the viewing direction by the atmosphere along the path between the sensor and sea surface (atmospheric path radiance).

Of these three radiance sources, the desired measurement is L_w, referred to in this report simply as ocean color. L_w carries information about the biological and chemical constituents in the near-surface waters. To obtain L_w, it is necessary to deduce and remove the contributions of surface reflection and atmospheric path radiance from the measured total, a process known as atmospheric correction. This is difficult because L_w is no more than 10 percent of L_{TOA}, as illustrated in Figure 1.2.

There are four levels of processing of satellite data:

Level 0: Raw data as measured directly from the spacecraft in engineering units (e.g., volts or digital counts).

Level 1: Level 0 data converted to TOA radiance using pre-launch sensor calibration and characterization information adjusted during the life of the mission by vicarious calibration and stability monitoring (for details see Chapter 3). For scientific applications, and in particular to generate

[1] See http://www.globalcarbonproject.org/carbonbudget/09/hl-full.htm#naturalSinks; accessed 1/7/2011.

[2] Primary production or photosynthesis converts carbon dioxide and water into carbohydrates and oxygen in the presence of light.

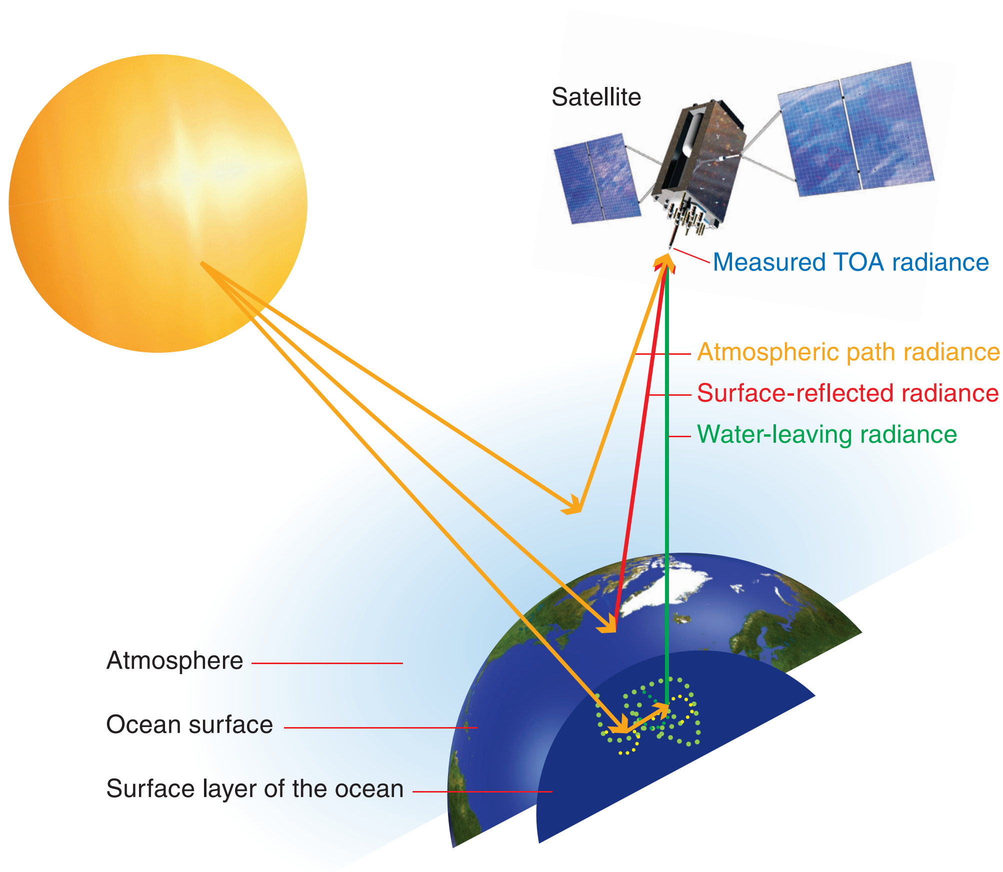


FIGURE 1.1 Qualitative illustration of the contributions of water-leaving radiance L_w surface glint, and atmospheric path radiance to the measured TOA radiance.
SOURCE: Adapted from http:www.gps.gov/multimedia/images/.

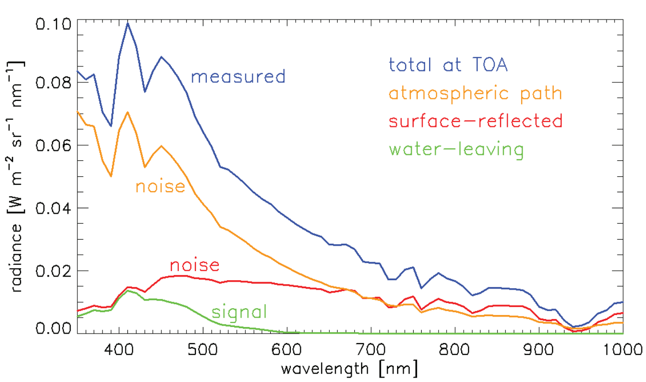


FIGURE 1.2 Quantitative illustration of the contributions of water-leaving, surface-reflected, and atmospheric path radiance to the measured TOA radiance. The water-leaving radiance—the signal—is at most 10 percent of the TOA radiance (simulations by the HydroLight and Modtran radiative transfer models using typical oceanic and atmospheric properties and 10-nm wavelength resolution).

Climate Data Records (CDRs), it is essential to archive Level 0 data, pre-launch calibration and characterization information, and post-launch calibration and stability monitoring data to enable periodic reprocessing of the raw data. Note: CDRs have been defined as "time-series of measurements of sufficient length, consistency, and continuity to determine climate variability and change," in the NRC report on CDRs from Environmental Satellites (NRC, 2004b).

Level 2: Level 2 data are generated from Level 1 data following atmospheric correction that are in the same satellite viewing coordinates as Level 1 data (i.e., the data have not been mapped to a standard map projection or placed on a grid). Level 2 data include L_w and derived products. Satellite viewing angles and other information are used to map any single Level 2 scene to a standard map projection (see definition of Level 3 data). L_w or ocean color radiance is generated from Level 1 radiance following atmospheric correction. Atmospheric correction for optically deep water[3] requires sensor measurements at near and short wave infrared wavelengths, ancillary measurements such as sea-level atmo-

[3] Optically deep water refers to water that is deep enough that the bottom reflectance does not contribute to the water-leaving radiance.

spheric pressure and wind speed, and models of atmospheric aerosol properties. The resulting measurement of ocean color radiance is a well-defined geophysical property whose measurement adheres to national and international standards. Ocean color radiance is considered the fundamental product from which all other ocean color products are derived.

Note: Although there is community consensus on the meaning of ocean color radiance, there are multiple approaches and algorithms for generating various derivative products such as measures of chlorophyll or primary production. Thus, it is critical that the path from Level 0 to Level 2 be well understood and documented and that the data to make these conversions be permanently archived. Periodic reprocessing begins with Level 0 data and uses knowledge of how sensor calibration has changed with time, better ancillary information, improved algorithms, and other lessons learned during the mission. Reprocessing is an essential mission requirement for generating quantitative data products, particularly climate data records. Moreover, standard atmospheric correction techniques for Level 2 processing are designed for open ocean waters and might not perform well in turbid coastal water, optically shallow water, and in coastal areas experiencing atmospheric pollutants and dust.

Level 3: Level 3 products are those that have been mapped to a known cartographic projection or placed on a two-dimensional grid at known spatial resolution. Level 0, 1, and 2 products are expressed in satellite coordinates and are not particularly useful to most applications of satellite data. Level 3 data products are often aggregated over time or space. These products are widely disseminated to scientific and operational users.

Level 4: Although gridded satellite data provide far better coverage in space and time than is possible with in situ data, most users want to validate such maps independently for their regions of study through comparisons with in situ data. Results derived from a combination of satellite data and ancillary information, such as ecosystem model output, are called Level 4 products.

New and better algorithms and ocean color products continue to emerge as technology and atmospheric corrections improve. As the scientific understanding advances regarding the relationships between ocean color radiance and the types of particulate and dissolved substances found in water, new and improved algorithms and ocean color products continue to emerge. Primary products (Figure 1.3) are derived with algorithms that rely exclusively on L_w and its relationship to the desired product, such as chlorophyll concentration. Secondary products require knowledge about their relationships to L_w as well as ancillary information obtained from other sensors, in situ observations, or models.

Chlorophyll concentration, the best known and most commonly used ocean color product, is an example of a primary product. The algorithms for determining it are well developed, and satellite-derived chlorophyll values have been validated at various scales, from single images to global composites, and used for a broad array of applications. Nevertheless, assumptions inherent to these algorithms need to be continuously tested and updated in a changing ocean. Particulate organic and inorganic carbon concentrations and Colored Dissolved Organic Matter (CDOM) absorption characteristics can also be derived from L_w spectra. A growing number of new primary products are being developed, such as inherent optical properties (e.g., phytoplankton absorption and backscatter coefficients) and concentrations of other suspended material, including various components of the particulate carbon and dissolved carbon pools in the ocean.

Marine net primary production,[4] a secondary product (Figure 1.3), illustrates the utility of ocean color measurements when combined with high-quality in situ data. Estimating net primary production requires ocean color measurements as well as other sources of information such as sea surface temperature or mixed layer depths. The importance of in situ data to enhance ocean color remote sensing will be revisited in Chapter 5. Scientists also use ocean color measurements in combination with other data to learn about the composition of phytoplankton. They accomplish this either by partitioning the total chlorophyll concentration into major size classes (pico-, nano- and micro-phytoplankton) or into major phytoplankton functional groups (diatoms, coccolithophores, blue-green algae, floating sargassum), or by identifying nuisance or harmful algal blooms. However, some methods for retrieving phytoplankton functional types are estimated directly from ocean color radiance (e.g., the diatom discrimination algorithm of Sathyendranath et al., 2004; the algorithm of Alvain et al., 2005).

RATIONALE FOR THIS STUDY

Over the past three decades, the oceanographic community has witnessed astounding growth in the capabilities of ocean color remote sensing. The Sea-viewing Wide Field-of-view Sensor-Moderate Resolution Imaging Spectroradiometer (SeaWiFS-MODIS) era from 1997 to present has provided scientists with a high-quality, well-calibrated L_w time-series from which to estimate chlorophyll concentration and primary production. As a result, for the first time, a climate-quality[5] data record can be compiled to demonstrate the strong link between interannual climate variability and the marine biosphere during the El Niño to La Niña transition on ocean-basin scales. Many of these recent discoveries and accomplishments in biological oceanography have been described in *Earth Observations from Space: The First 50*

[4] Net primary production quantifies the net conversion of carbon dioxide and water into carbohydrates and oxygen in the presence of light and represents the energy supply to the base of marine food webs.

[5] To demonstrate long-term trends in a time-series with large natural interannual variability, the data record requires very high accuracy. For the ocean color climate record, accuracy requirements are discussed in Chapters 3-5.

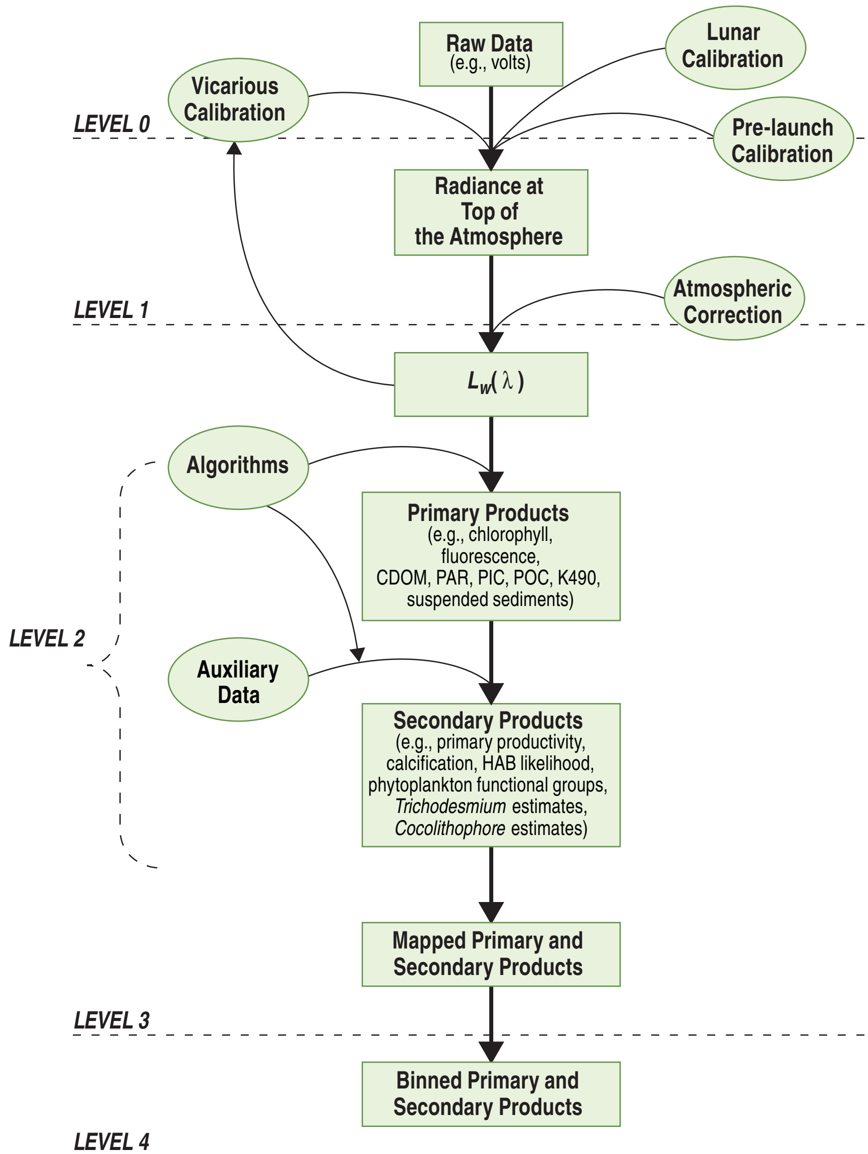


FIGURE 1.3 Ocean color radiance is used to derive products directly or indirectly. Secondary products are based on the primary products and ancillary data. These products are then used to address scientific and societal questions. Some satellite missions apply the vicarious calibration when processing Level 2 data. (CDOM: Colored Dissolved Organic Matter; PAR: Photosynthetically Available Radiance; PIC: Particulate Inorganic Carbon; POC: Particulate Organic Carbon; K490: diffuse attenuation coefficient at 490 nm; HAB: Harmful Algal Bloom).

Years of Scientific Achievements (NRC, 2008a) and a recent International Ocean Colour Coordinating Group report (IOCCG, 2008).

To sustain and build on these achievements, the climate research community requires access to uninterrupted climate-quality data records for the marine biosphere. Such records are central to validating new, more sophisticated climate models that incorporate biogeochemical processes, such as primary production, and validating and improving the accuracy of products in a changing ocean.

Moreover, as detailed in the research community's plan entitled *Advanced Plan for the Ocean Biology and Biogeochemistry Program* (NASA, 2007); continued support for ocean color remote sensing is needed to improve computer-based modeling of ecosystem dynamics. Ocean color remote sensing data are necessary to build accurate and useful models related to climate change, which will increase our understanding of variability of in situ organic and inorganic carbon constituents; continental shelf ecosystem dynamics and variability of the mixed-layer thickness; and variability of particulates and aerosols in the ocean and atmosphere. Furthermore, as the length of the climate-quality ocean color data record grows, its intrinsic value for recording long-term changes in the marine ecosystem also increases.

It is important to note that, with the availability of routine measurements and with free and easy access to ocean color data, the user community has expanded dramatically to include state and federal coastal and fisheries resource managers who depend on the data for ecosystem monitoring (e.g., coral ecosystems and harmful algal blooms). Therefore, any gap in the time-series—regardless of how short—would be detrimental not only to the ocean color and climate research community but also to resource managers.

THE STUDY'S TASK

To assess the risk for losing access to high-quality L_w data and to identify mitigation options, the National Oceanic and Atmospheric Administration (NOAA), NASA, the National Science Foundation (NSF), and the Office of Naval Research (ONR) asked the National Academy of Sciences (NAS) to convene an ad hoc committee. The committee was asked to assess the requirements to sustain global ocean color research and operational applications (see Box 1.1 for the statement of task).

Since the task statement was written, significant changes related to ocean color remote sensing have occurred that have shifted the baseline for this study. Most significantly, in February 2010, the White House ordered the restructuring of the National Polar-orbiting Operational Environmental Satellite System (NPOESS) program and a separation of the civilian programs from the Department of Defense (DOD) program. The civilian portion of the NPOESS program has become the Joint Polar Satellite System (JPSS). In addition, the latest Visible Infrared Imager Radiometer Suite (VIIRS) characterization yielded positive results and cautious optimism about the sensor's performance (see Chapter 3 for a detailed discussion). In more good news, planning has started at NASA for a new ocean color mission, the Pre-Aerosol-Clouds-Ecosystem (PACE) mission, with a launch date of 2019 or later.

In December 2010, the SeaWiFS mission ceased operation. Thus the ocean color community lost the sensor that had become the gold standard for ocean color remote sensing.

Lastly, the Deep Water Horizon oil spill that began in April 2010 was a stark reminder of coastal communities' dependence on healthy marine ecosystems. The spill reinforced the ways in which human activities can jeopardize those ecosystems and the communities that rely on them for their livelihoods and survival. Remote sensing from both planes and satellites was critical in monitoring and projecting the evolution of the oil slick and highlighted the importance of ocean color remote sensing to an oil spill response.

REPORT ROADMAP

To address the task, this report identifies in Chapter 2 the research and operational applications for ocean color products and the data specifications to generate them. Chapter 3 evaluates lessons from past and current sensors and missions. Based on these lessons learned, the committee establishes the minimum requirements for sustaining the capability to obtain remotely sensed ocean color data. Chapter 4 assesses the gaps in meeting the requirements, evaluates current and future capabilities of U.S. and foreign missions, and provides options to minimize the risk of a data gap in the near term. Chapter 5 provides a long-term view; it describes challenges in meeting all research and operational requirements and lists many existing opportunities for building on lessons learned and advancing current capabilities.

Box 1.1
Statement of Task

Continuity of satellite ocean color data and associated climate research products are presently at significant risk for the U.S. ocean color community. Temporal, radiometric, spectral, and geometric performance of future global ocean color observing systems must be considered in the context of the full range of research and operational/application user needs. This study aims to identify the ocean color data needs for a broad range of end users, develop a consensus for the minimum requirements, and outline options to meet these needs on a sustained basis.

An ad hoc committee will assess lessons learned in global ocean color remote sensing from the SeaWiFS/MODIS era to guide planning for acquisition of future global ocean color radiance data to support U.S. research and operational needs. In particular, the committee will assess the sensor and system requirements necessary to produce high-quality global ocean color climate data records that are consistent with those from SeaWiFS/MODIS. The committee will also review the operational and research objectives, such as described in the Ocean Research Priorities Plan and Implementation Strategy, for the next generation of global ocean color satellite sensors and provide guidance on how to ensure both operational and research goals of the oceanographic community are met. In particular the study will address the following:

1. Identify research and operational needs, and the associated global ocean color sensor and system high-level requirements for a sustained, systematic capability to observe ocean color radiance (OCR) from space;
2. Review the capability, to the extent possible based on available information, of current and planned national and international sensors in meeting these requirements (including but not limited to: VIIRS on NPP and subsequent JPSS spacecrafts; MERIS on ENVISAT and subsequent sensors on ESA's Sentinel-3; S-GLI on JAXA's GCOM-C; OCM-2 on ISRO's Oceansat-2; COCTS on SOA's HY-1; and MERSI on CMA's FY-3);
3. Identify and assess the observational gaps and options for filling these gaps between the current and planned sensor capabilities and timelines; define the minimum observational requirements for future ocean color sensors based on future oceanographic research and operational needs across a spectrum of scales from basin-scale synoptic to local process study, such as expected system launch dates, lifetimes, and data accessibility;
4. Identify and describe requirements for a sustained, rigorous on-board and vicarious calibration and data validation program, which incorporates a mix of measurement platforms (e.g., satellites, aircraft, and in situ platforms such as ships and buoys) using a layered approach through an assessment of needs for multiple data user communities; and
5. Identify minimum requirements for a sustained, long-term global ocean color program within the United States for the maintenance and improvement of associated ocean biological, ecological, and biogeochemical records, which ensures continuity and overlap among sensors, including plans for sustained rigorous on-orbit sensor inter-calibration and data validation; algorithm development and evaluation; data processing, re-processing, distribution, and archiving; as well as recommended funding levels for research and operational use of the data.

The review will also evaluate the minimum observational research requirements in the context of relevant missions outlined in previous NRC reports, such as the NRC "Decadal Survey" of Earth Science and Applications from Space. The committee will build on the Advance Plan developed by NASA's Ocean Biology and Biogeochemistry program and comment on future ocean color remote sensing support of oceanographic research goals that have evolved since the publication of that report. Also included in the review will be an evaluation of ongoing national and international planning efforts related to ocean color measurements from geostationary platforms.

2

Sustaining and Advancing Ocean Color Research and Operations

Ocean color satellites provide a unique vantage point for observing the changing biology in the surface ocean. Space observations have transformed biological oceanography (Box 2.1) and are critical to advance our knowledge of how such changes affect important elemental cycles, such as the carbon and nitrogen cycles, and how the ocean's biological processes influence the climate system. In addition, ocean color remote sensing allows scientists to assess changes in primary production, which forms the base of the marine food chain. Thus, continuous satellite observation of ocean color is essential to monitoring the health of the marine ecosystem and its ability to sustain important fisheries, especially in a time of global change. Any interruption in the ocean color record would severely hamper the work of climate scientists, fisheries and coastal resource managers, and an expanding array of other users, from the military to oil spill responders.

It is increasingly recognized that despite the ocean's vastness, its resilience is finite. The new National Ocean Policy recognizes the many threats to pelagic and coastal marine environments from human activities. Most notably, coral reef environments are degrading because of rising water temperatures, ocean acidification, and other environmental stressors. Overfishing, coupled with environmental variability and habitat loss, threatens many fish stocks. Other human-caused disturbances include chronic beach contamination, hypoxia in estuaries and the coastal ocean, and water quality degradation due to industrial, agricultural, and residential pollution. The 2010 BP oil spill in the Gulf of Mexico is a prime example of a severe anthropogenic impact on the marine environment.

To support the goals and priorities outlined in the National Ocean Policy (CEQ, 2010) and Ocean Research Priorities Plan (JSOST, 2007), continued monitoring of the ocean's ecosystems on a global scale is essential. The continuity, global coverage, and high temporal and spatial resolution of ocean color products make remote sensing a critical tool for monitoring and characterizing ocean biology and marine ecosystems. Most of the spatial features that are important for marine ecosystems, i.e., ocean fronts, eddies, convergence zones, river plumes, and coastal regions, cannot be brought into full view and studied without satellite observations. Similarly, ocean color products are crucial for making observations frequently enough to study the timing of processes that can have important effects on living marine resources, such as upwelling, harmful algal blooms[1] (HAB), seasonal transition, El Niño events, and oil spills.

The use of remotely sensed ocean color products has become ubiquitous in oceanography and marine resource management. This chapter, while not comprehensive, provides examples of the growing array of research and societal applications and related product requirements. In other words, the chapter details the research and resource management questions that ocean color products can help answer. Applications such as coastal marine resource monitoring require near-real time products at fine spatial and temporal scales available from Geostationary Earth Orbit (GEO) satellites (discussed in Appendix D), while others require global, long-term observations provided by traditional sun-synchronous Low Earth Orbit (LEO) satellites. As detailed below, different types of ocean color sensors will be required to meet these diverse demands.

RESEARCH AND SOCIETAL APPLICATIONS OF OCEAN COLOR PRODUCTS

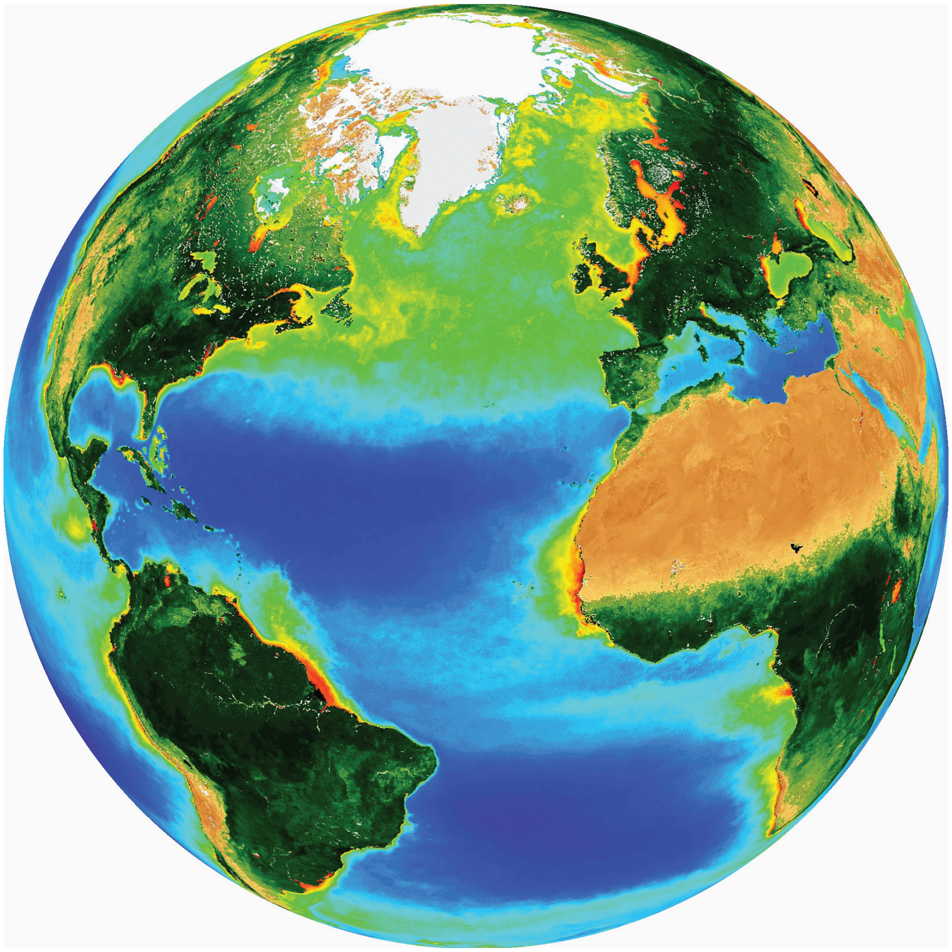
Many basic research and ecosystem management applications of ocean color have long time frames. Users may have to wait weeks or months for data to be processed, and studies can take years before long-term processes and changes can be detected. But ocean color is also critical to users who rely on it for solving societal challenges on a near-real time basis.

[1] An algal bloom is defined as a rapid accumulation of algal biomass.

Box 2.1
The Unique Vantage Point from Space

"The ability to derive global maps of chlorophyll-a concentration (milligrams per cubic meter) in the upper ocean from ocean color sensors was a groundbreaking achievement for the oceanographic community" (see figure below; NRC, 2008a).

The unique vantage point from space has revolutionized Earth sciences in general. For the first time, scientists have been able to obtain a global synoptic view of the biomass of phytoplankton in the ocean. This unique observing platform has also allowed scientists for the first time to visualize and study dynamic features, such as mesoscale eddies and ocean fronts, and their impact on ocean biology.



Map of chlorophyll concentration (milligrams per cubic meter) in the upper Atlantic Ocean derived from data obtained by the Sea-viewing Wide Field-of-view Sensor.
SOURCE: SeaWiFS Project, NASA Goddard Space Flight Center, and GeoEye.

Research Applications for Ocean Color Products

Tracking changes in global marine plant biomass is fundamental to ocean biology. Satellite data provide an incredibly powerful tool for observing and quantifying changes in ocean plant biomass over various spatial and temporal scales and for monitoring climate variations and trends. Most of the plant biomass in the ocean comprises microscopic photosynthetic organisms (phytoplankton) that are moved around, mixed, and dispersed by ocean currents and other physical processes. Phytoplankton are different from land plants, which have a large standing biomass that includes large amounts of carbon tied up in structures such as roots and trunks. Phytoplankton standing biomass is comparatively low (about 0.1 percent of land plant biomass) but they grow quickly—in some cases doubling in a single day. Grazing rates on phytoplankton can also be very high. Thus, compared with land plants, phytoplankton biomass is highly variable in space and time and can change much more rapidly in response to changing environmental conditions (Chavez et al., 2011). The dynamic nature of the system, coupled with the difficulty of routinely sampling the global ocean from ships or moorings, demonstrates the incomparable value of remotely sensed ocean color data for tracking phytoplankton biomass variability in different ocean regions over time. Sustaining this record is essential to test many hypotheses about long-term changes in biogeochemical cycles. One example is the current hypothesis that future sea surface warming associated with long-term climate change will result in a decrease in algal biomass, which could affect the ocean's ability to take up atmospheric CO_2 and support marine life that includes valuable fish stocks.

Climate and Biogeochemical Research Applications

How does the ocean's biology affect the carbon cycle and other biogeochemical cycles?

Carbon is continuously exchanged between the ocean, atmosphere, and land (Figure 2.1). Carbon enters the surface ocean and is dissolved in the water. Compared to the intermediate or deep ocean, the carbon residence time in the surface ocean is relatively short. The biggest reservoir of carbon is in the intermediate and deep ocean. The solubility and biological pumps combined represent the net uptake of carbon by the ocean. When cold, dense water is formed in high latitude, the water containing the dissolved carbon sinks to the deep ocean (solubility pump). Phytoplankton take up some of the carbon in the sun-lit surface layers of the ocean during photosynthesis to produce particulate and dissolved organic carbon. A fraction of this particulate organic carbon can sink (biological pump) to the abyssal plains; an even smaller fraction is buried in the sediments. In these ways, CO_2 is removed from surface waters and moved to deep waters and sediments, where it remains for centuries to millennia. It is critical that we continue to improve our understanding of these processes in the ocean, as they are key to the global carbon cycle and other biogeochemical cycles that are essential to life on Earth.

Ocean color observations are important for verification of numerous models that show that the response of ocean biology to changes in ocean circulation may significantly impact the air-sea balance of CO_2 in the future (e.g., Sarmiento and Le Quéré, 1996; Sarmiento et al., 1998; Joos et al., 1999; Matear and Hirst, 1999; Plattner et al., 2001; Friedlingstein et al., 2006) and for determining if changes are actually occurring. In addition, ocean color data provide various methods to identify areas of nitrogen fixation (Subramanium et al., 2002; Westberry et al., 2005), which have the potential to alter global biogeochemical cycles.

Ship-based observations provide insufficient spatial coverage to quantify these biogeochemical processes. Because phytoplankton blooms and their associated areas of high productivity are such large-scale yet short-lived phenomena, it is impossible to survey large enough areas of the ocean with ships in order to map phytoplankton productivity and changes in the carbon cycle. Only since the availability of ocean color satellites have scientists been able to routinely estimate global net primary production on weekly to interannual time scales and thus to detect global trends (NRC, 2008a).

Biological uptake of nutrients and carbon at the surface of the ocean plays a crucial role in linking the carbon-rich reservoir of the deep ocean with the atmosphere. Indeed, there are indications that changes in Southern Ocean circulation, together with the response of biology to these changes, may already be affecting the oceanic uptake of CO_2 from the atmosphere (Le Quéré et al., 2007; Lovenduski et al., 2007, 2008). The Southern Ocean is estimated to have weakened as a CO_2 sink between 1984 and 2004, relative to the trend expected from the corresponding large increase in atmospheric CO_2 (Le Quéré et al., 2007). The increase in dissolved CO_2 in the surface ocean is also making the ocean more acidic, which has important implications for many marine organisms and ecosystems (Doney et al., 2009; NRC, 2010). Ocean acidification has the potential to reduce rates of calcification, which could lower the efficiency of the biological pump, because de-calcified organisms sink less rapidly and therefore transport organic carbon to the deep sea at a slower rate. These possible effects of ocean acidification are only now beginning to be investigated (Hofmann and Schellnhuber, 2009).

While almost all marine primary production occurs in the sun-lit surface layer of the ocean, large pools of macronutrients are found in the deep ocean. In nutrient-limited regions of the surface ocean, vertical upwelling brings nutrients to the surface and drives primary production (Lewis et al., 1986). With some exceptions, nitrate is the nutrient that limits phytoplankton growth in the surface ocean on short time scales (Lewis et al., 1986). Some organisms

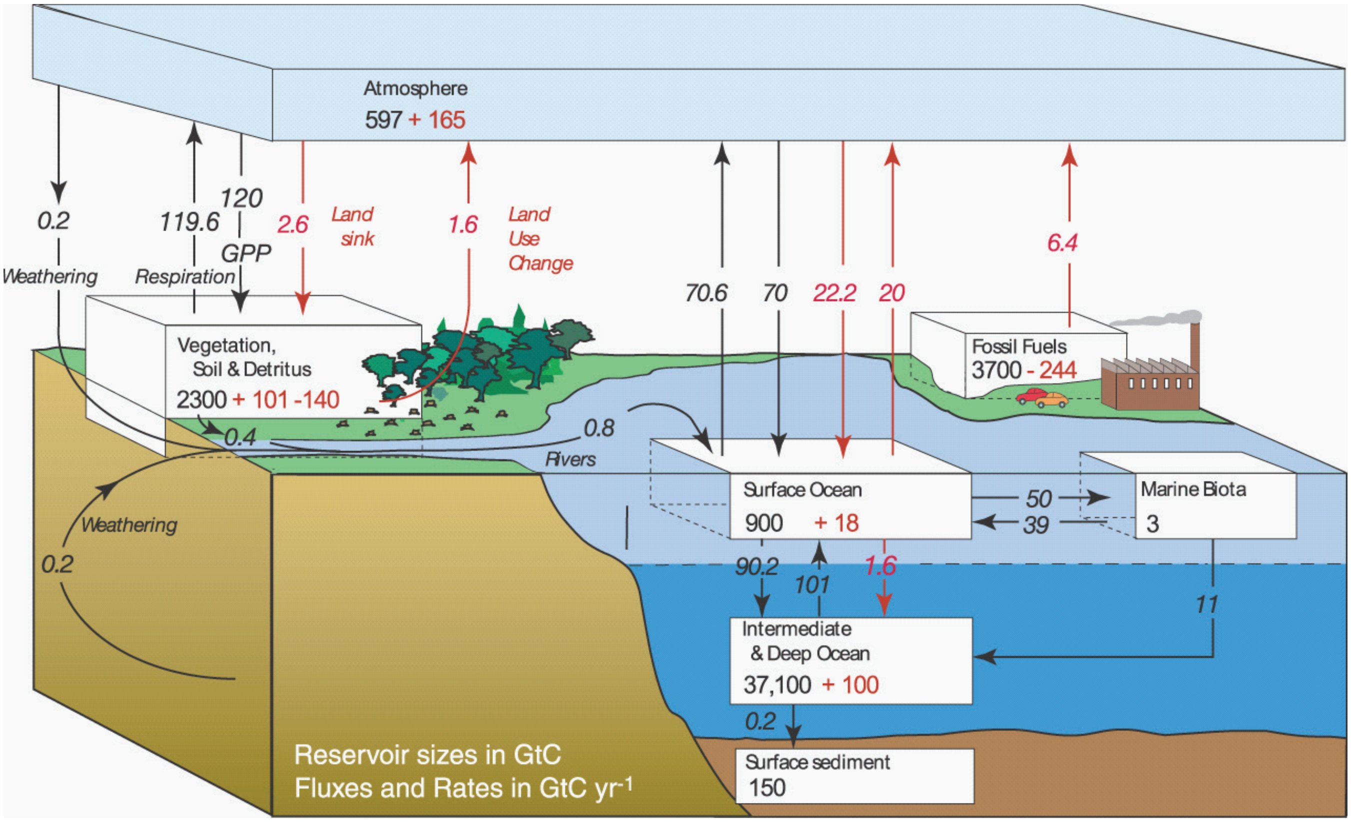


FIGURE 2.1 "The global carbon cycle for the 1990s, showing the main annual fluxes in Gigatons of Carbon (GtC) yr^{-1}: pre-industrial 'natural' fluxes in black and 'anthropogenic' fluxes in red (modified from Sarmiento and Gruber, 2006, with changes in pool sizes from Sabine et al., 2004). The net terrestrial loss of –39 GtC is inferred from cumulative fossil fuel emissions minus atmospheric increase minus ocean storage. The loss of –140 GtC from the 'vegetation, soil, and detritus' compartment represents the cumulative emissions from land use change (Houghton, 2003), and requires a terrestrial biosphere sink of 101 GtC (in Sabine et al., given only as ranges of –140 to –80 GtC and 61 to 141 GtC, respectively; other uncertainties given in their Table 1). Net exchanges of anthropogenic carbon with the atmosphere are based on IPCC WGI Chapter 7. Gross fluxes generally have uncertainties of more than ±20 percent but fractional amounts have been retained to achieve overall balance when including estimates in fractions of GtC yr^{-1} for riverine transport, weathering, deep ocean burial, etc. 'GPP' is annual gross (terrestrial) primary production. Atmospheric carbon content and all cumulative fluxes since 1750 are as of end 1994."
SOURCE: IPCC, 2007; used with permission from Intergovernmental Panel on Climate Change.

(e.g., *Trichodesmium*) can thrive in nitrate-depleted waters by fixing dissolved nitrogen. The fixed nitrogen becomes subsequently available to other photosynthetic organisms and might shift the ecosystem toward phosphorus limitation (Karl et al., 1997; Cullen, 1999; Tyrrell, 1999).

Different methods exist to identify nitrogen fixation from satellite ocean color remote sensing (Subramanium et al., 2002; Westberry et al., 2005). For example, large blooms of chlorophyll-containing phytoplankton in the southwest Pacific, observed by both Coastal Zone Color Scanner (CZCS) and the Sea-viewing Wide Field-of-view Sensor (SeaWiFS), have been identified as *Trichodesmium* blooms (Dupouy et al., 1988, 2000; Westberry and Siegel, 2006). Satellite images also revealed large blooms in late summer in the oligotrophic Pacific northeast of Hawaii (Wilson and Qiu, 2008). Based on biological observations made in situ, those blooms have been attributed to nitrogen fixers or vertically migrating diatom mats (Wilson et al., 2008). The nitrogen provided by nitrogen fixation could contribute substantially to the total available nitrogen for oceanic new production (Capone et al., 1997; Gruber and Sarmiento, 1997; Karl et al., 1997). While total nitrogen fixation is estimated at 110 Tg y^{-1} (Gruber and Sarmiento, 1997), nitrogen fixation from *Trichodesmium* species is estimated at 80 Tg y^{-1} (Capone and Carpenter, 1999). Improving our understanding of the spatial and temporal patterns and production of these blooms is essential because of their size, duration and potential to alter global climate through changes in the biological pump (Michaels et al., 2001; Sañudo-Wilhelmy et al., 2001).

Ocean color data have also revealed extensive open-ocean blooms in the northeast Pacific Ocean (Wilson, 2003; Wilson et al., 2008) and southeast of Madagascar (Longhurst, 2001; Srokosz et al., 2004; Uz, 2007). These blooms are unusual in that they occur in nutrient-depleted regions of the ocean, and the physical mechanisms that deliver nutrients to support them remain unknown. The discovery highlights how little we know about the open ocean and how our understanding of the complexity of marine ecosystems evolves. Ocean color data have played and will play a crucial role in the discovery process.

How is the global marine phytoplankton biomass changing in response to short-term climate variability and long-term climate trends?

SeaWiFS was launched in August 1997 and contributed to the understanding of the subsequent 1997-1998 El Niño (IOCCG, 2008). The satellite data combined with in situ data from the equatorial Pacific helped scientists understanding El-Niño Southern Oscillation (ENSO) dynamics and their impacts on ecosystems. For example, the deepening of the thermocline and associated weakening of upwelling along the equator and in the coastal ecosystems lowers ocean productivity and causes substantial decreases in the anchovy fisheries of Peru and Chile (Alamo and Bouchon, 1987; Escribano et al., 2004).

Moreover, satellite ocean color products have demonstrated that El Niño effects are not restricted to the equatorial and coastal upwelling regions (IOCCG, 2008). For example, during the 1997-1998 ENSO event, the Transitional Zone Chlorophyll Front, an important region of the North Pacific ecosystem, was shifted about 5°S of its regular position (Bograd et al., 2004). Also, decreased chlorophyll concentrations were observed across most of the subtropical Pacific (Wilson and Adamec, 2001). This basin-scale response, detected with satellite observations, had not been previously detected with in situ observations.

One of the most important challenges for marine science is to distinguish ocean changes caused by interannual variability (e.g., ENSO variability) from trends caused by long-term climate changes or other human effects (Chavez et al., 2011). Recent satellite studies show a general decrease in chlorophyll either in the mid-ocean gyres with some regional variability (Vantrepotte and Melin, 2009) or in the "stratified parts of the low-latitude ocean" (Behrenfeld et al., 2006). The same studies show chlorophyll increases in other parts of the world's ocean, based on SeaWiFS observations (Antoine et al., 2005; Gregg et al., 2005; Behrenfeld et al., 2006; Polovina et al., 2008; Vantrepotte and Melin, 2009). Sea surface temperature (SST)-based indexes of stratification show a relation between decreasing chlorophyll and NPP and increasing stratification, which suggests a link between reduced phytoplankton abundance and a gradual warming of ocean surface waters (Behrenfeld at al., 2006). Devred et al. (2009) showed that in the Northwest Atlantic, the trends differed among ecological provinces studied.

SeaWiFS was launched during the ENSO event that began in 1997—one of the strongest events of the twentieth century—and thus the initial years of the record are strongly biased by the ENSO effects. Analyses of SeaWiFS data with CZCS observations from 1979 to 1983, and SST observations from both periods, suggest that the basin-scale phytoplankton responses were related to the Pacific Decadal Oscillation and the Atlantic Multidecadal Oscillation with little evidence to suggest long-term trends (Martinez et al., 2009). Comparing satellite records with the results of climate models incorporating ocean ecosystems and biogeochemical cycles indicate that the magnitude of the chlorophyll changes observed during the SeaWiFS era were not unusual. Comparable changes have occurred during multiple-year intervals in the past and can be accounted for by interannual variability (Henson et al., 2010; Yoder et al., 2010).

Because the time-series of remotely sensed phytoplankton chlorophyll is not long enough to detect long-term trends in response to climate change (see Box 2.2), Secchi disk

Box 2.2
How Long Before a Time-Series Can Reveal Long-Term Climate Trends?

Using the methodologies of trend detection, Henson et al. (2010) concluded that 40 years of observations will be required to sort out the effects of natural modes of climate variability, such as ENSO, from trends related to a changing climate and changing ocean. Climate data often contain autocorrelation and large interannual and decadal natural variability that tend to increase the number of years necessary for trend detection (Tiao et al., 1990; Weatherhead et al., 1998). Other factors that make trend detection in climate data challenging include a change in the measurement procedures (e.g., instrument replacement) or a data gap. Changes in measurement procedures can affect data by introducing artificial shifts and/or gradual bias and thus affect the ability to detect trends (Peterson et al., 1998). Such biases can be confused with the magnitude of a real trend and must be corrected for or otherwise taken into account while estimating the trend. Weatherhead et al. (1998) take gaps in the data into account and show that in the worst scenario, the years required to detect a trend can increase by 50 percent.

To arrive at the 40-year time frame, Henson et al. (2010) assume that there will be no interruption in satellite data. This number varies according to the satellite data characteristics and the expected trend magnitude (estimated by using three ocean biogeochemical models) in 14 different regions. If the continuity of measurements is broken over this period, as many as 20 additional years of observations will be necessary. Distinguishing the effects of ocean cycles from long-term trends, and identifying the implications for marine ecosystems, is a major challenge that ocean satellites can help to resolve.

records that date to 1899 have been used as a proxy for phytoplankton chlorophyll (Falkowski and Wilson, 1992; Hou et al., 2007; Boyce et al., 2010). These records have been interpreted as showing an annual decline of about 1 percent in global median chlorophyll (Boyce et al., 2010), which would have major ramifications for the global marine ecosystem. Although the conclusions of Boyce et al. (2010) are challenged by some (Mackas, 2011; McQuatters-Gollop et al., 2011; Rykaczewski and Dunne, 2011), they are consistent with the hypothesis (see also Box 2.3) that increasing ocean warming contributes to changes in the marine ecosystems, which has implications for biogeochemical cycling, fishery yields, and ocean circulation. However, longer records of remotely sensed chlorophyll will be required to detect associated trends in phytoplankton biomass and to improve the estimates of regional rates of change. Assembling those records will be possible only with continuous satellite observations of ocean color. Future research to detect trends in phytoplankton chlorophyll will also have to consider changes in the phytoplankton assemblages and in the relative contribution to the L_w signal from chlorophyll and color dissolved organic matter (CDOM) (Dierssen, 2010). The color of the ocean is driven by the optical properties of the dissolved and particulate materials (including living phytoplankton) in seawater, modulated by the optical properties of pure seawater itself. Thus, the ocean color signals will reflect the combined influences of these materials, all of which vary in abundance, in time, and in spectral characteristics. Detecting these trends and the changes in the relative contribution from CDOM will only be possible with advanced sensor capabilities such as additional spectral bands.

Box 2.3
How Might Climate Change Affect the Ocean's Biology in the Future?

Bopp et al. (2001) carried out the first modeling study to demonstrate how increased stratification and associated processes tend to reduce nutrient supply, and thus biological productivity, in low latitudes. At the same time, these climate-related changes increase the length of the growing season and thus biological productivity in high latitudes, where nutrients are more abundant and less affected by the increased stratification (Bopp et al., 2001). Sarmiento et al. (2004) compared a suite of coupled climate models and illustrated how changes in ocean properties shift the boundaries of biomes in the ocean. More recent studies (e.g., Schneider et al., 2008; Steinacher et al., 2010) compared model simulations that have been used to predict ocean ecosystems. The differences between the models are large; subtle interactions between different drivers of biology and the response of these drivers to climate change yield results that may seem counterintuitive (e.g., Rykaczewski and Dunne, 2010).

Testing of the models with chlorophyll and primary production estimated on the basis of satellite ocean color observations is crucial for developing the models and increasing our confidence in them (Doney et al., 2009), particularly with regard to changes in the seasonal cycle. However, because the chlorophyll: carbon ratio can change substantially in response to changing light levels, it is possible that chlorophyll-based algorithms will not capture relatively small changes in net seasonal productivity. Validation of new products—such as carbon biomass from particulate backscatter (Behrenfeld et al., 2005) or from chlorophyll (Sathyendranath et al., 2009), particle size structure from the backscatter spectrum (Kostadinov et al., 2009), and production associated with individual functional groups (Alvain et al., 2008; Uitz et al., 2010)—is likely to be critical in mechanistically improving the models and in distinguishing changes associated with anthropogenic climate change from those associated with natural variability (Henson et al., 2010).

How does ocean color affect radiative heat transfer in the climate system?

To predict the climate accurately, SST has to be simulated correctly. Because older models had such coarse vertical resolution in the upper ocean, variability in the absorption by chlorophyll and CDOM did not make much of a difference in computing depth-dependent heating rates. Recent research has shown that the absorption of light by chlorophyll and CDOM can have a major effect on SST and resulting climate predictions (Marzeion et al., 2005). This discovery demonstrates that the current distribution of ocean color is key to determining the pattern of tropical SSTs. Moreover, as much of the absorbing material is CDOM rather than chlorophyll (Siegel et al., 2005a), these results highlight the importance of understanding CDOM dynamics and how they may change under different climates. There is a rapidly growing recognition of the importance of including these processes in climate models, using primarily satellite-based observations of ocean color for re-interpreting observations, for reanalysis simulations and ecosystem models, and for simulating future conditions.

Studies that examine the role of ocean color in determining large-scale climate changes through altering the absorption profile of solar radiation have yielded somewhat inconsistent results. Some model studies resulted in cooling of the equatorial waters (Nakamoto et al., 2001; Sweeney et al., 2005) while others yielded increased surface heating (Marzeion et al., 2005; Lengaigne et al., 2007) when a realistic distribution of chlorophyll-dependent absorption was included in their models.

Recent work suggests that the ambiguity may arise from the fact that different regions respond differently to perturbations in shortwave absorption. In the relatively stagnant eastern oceanic margins, associated with the oxygen minimum zones, trapping solar radiation closer to the surface cools deeper waters. Because the colder water is essentially trapped in place, it results in cooling the marginal zone (Gnanadesikan and Anderson, 2009). That also results in stabilizing the Walker[2] circulation and dampening El Niño (Anderson et al., 2009). In contrast, trapping solar radiation closer to the surface in the gyres results in surface heating, as the deeper, cooler waters tend to be carried away and brought up along the equator. That in turn tends to spin down the Hadley cells, allowing convection to move more freely in the tropics and increasing the amplitude of ENSO. At high latitudes a different scenario is observed, where phytoplankton blooms result in increased cloud cover and cloud albedo, which decreases the local precipitation and incoming solar radiation (Krüger and Graßl, 2011). Ocean color remote sensing will be an important tool to understanding these ocean-climate feedbacks.

How variable in space and time are plant physiology and functional groups?

Some ocean color satellites can measure fluorescence emitted by phytoplankton (Moderate Resolution Imaging Spectroradiometer [MODIS] and Medium-Resolution Imaging Spectrometer [MERIS]) (Gower et al., 2004; Gower and King, 2007; Behrenfeld et al., 2009). This fluorescence measurement can be used to assess phytoplankton physiology, especially as it relates to nutrient availability and irradiance (Kromkamp and Peene, 1995). A global analysis of chlorophyll fluorescence using MODIS data found generally high values associated with waters depleted in iron, and low fluorescence where other environmental factors control growth (Behrenfeld et al., 2009; Sathyendranath et al., 2009). An important component of phytoplankton physiology is the cellular ratio of chlorophyll to carbon (Chl:C). Because changes in light and temperature conditions can impact the Chl:C ratio, observed changes in chlorophyll are not always an accurate proxy for changes in phytoplankton biomass. Satellite ocean color data can be used to derive global fields of the Chl:C ratio, which have strong seasonality and variability driven by light, nutrients, and temperature (Behrenfeld et al., 2005).

Among the big challenges in ocean color research is to move beyond chlorophyll and to identify specific types and functional groups of phytoplankton on the basis of L_w data (e.g., Brewin et al., 2011). Identifying functional groups is important because of their different effects on ecosystem processes, such as their different capabilities for exporting organic matter, including carbon, to depth. Therefore, it is important to understand where the functional groups are found, how they vary interannually, and how they might respond to climate change.

Because different phytoplankton species have different optical properties, they can sometimes be identified with careful analyses of the different wavebands of ocean color. For example, coccolithophores are highly reflective. Under bloom conditions they turn the water a turquoise color that appears as a milky colored patch in satellite images that can be easily discerned by remote sensing. Coccolithophores were the first type of phytoplankton to be specifically isolated by using satellite data (Holligan et al., 1983a; Ackleson et al., 1994; Brown and Yoder, 1994; Brown and Podesta, 1997; Tyrrell, 1999; Gordon et al., 2001; Smyth et al., 2002). There also has been some success in identifying *Trichodesmium* by using satellite ocean color data (Subramaniam et al., 2001; Westberry et al., 2005; Westberry and Siegel, 2006). Ocean color data also have been used to identify functional groups of phytoplankton, such as haptophytes, *Prochlorococcus*, cyanobacteria, and diatoms (Sathyendranath et al., 2004; Alvain et al., 2005, Aiken et al., 2007) and to infer the distribution of different size classes of phytoplankton (Ciotti and Bricaud, 2006; Devred et al., 2006; Loisel et al., 2006; Uitz et al., 2006; Hirata et al., 2008; Kostadinov et al., 2010). Increasing the spectral resolution of satellite sensors will improve methods for detecting functional groups from space.

Fisheries and Ecosystem-Based Management

Sustaining the health and resilience of our marine ecosystems is a high national priority. With the creation of the first *National Policy for the Stewardship of the Oceans, Our Coasts, and the Great Lakes* (CEQ, 2010) it is now the policy of the nation to "protect, maintain, and restore the health and biological diversity of ocean, coastal, and Great Lakes ecosystems and resources" (CEQ, 2010).

The National Oceanic and Atmospheric Administration's (NOAA) National Marine Fisheries Service (NMFS) is responsible for conserving, protecting, and managing living marine resources in order to maintain a healthy, functional marine ecosystem and the economic opportunities it provides. In this context, NOAA's fisheries service encompasses commercial fish stocks and all living marine resources (LMR), including threatened and endangered species of fish, marine mammals and invertebrates, and the harvesting and management of commercial fish species. Whereas satellite ocean color products have been used to help harvest fish more efficiently in India and Japan (Wilson et al., 2008; Saitoh et al., 2009), the following section focuses on how ocean color products are used in the United States to assess and manage fisheries and ecosystem health.

[2] Walker circulation refers to a conceptual model of the air circulation in the tropics. It was first described by Gilbert Walker. According to this model, the air moves along the surface of the Pacific Ocean from east to west, caused by a pressure gradient force that results from a high pressure system over the Eastern Pacific and a low pressure system over Indonesia. The air circulates back at high altitude towards the East, closing the loop of the Walker circulation.

How does environmental variability affect fish stocks and ecosystem health?

Fish stock assessments provide the technical basis for setting annual fish quotas and other management measures to achieve optimum yield while avoiding overfishing and ecosystem harm. At a minimum, a quantitative stock assessment requires monitoring of catch, abundance, and biological characteristics of the stock. Achieving a balance between exploitation and conservation requires substantial information about the stock, its fishery, the ecosystem, and the habitat. However, the environmental factors influencing fish populations are complex, and many remain poorly understood.

Ocean color products are helping to answer a fundamental research question in fisheries oceanography: How does environmental variability affect annual recruitment?[3] Because most fish have a planktonic larval stage, successful recruitment depends on the availability of a suitable food source such as phytoplankton. Thus, fish reproduction tends to coincide with the seasonal peak in phytoplankton abundance (IOCCG, 2008). The Cushing-Hjort or match-mismatch hypothesis suggests that recruitment success is related to the match in timing between spawning and the seasonal phytoplankton bloom (Cushing, 1990). Because of the limited spatial and temporal resolution of traditional ship-based measurements, testing that hypothesis requires satellite-based observations. On the Nova Scotia Shelf, for example, highly successful year classes of haddock were associated with exceptionally early spring blooms of phytoplankton, which supports the match-mismatch hypothesis (Platt et al., 2003). Similarly, the timing of the spring bloom and the growth rate of shrimp are correlated (Fuentes-Yaco et al., 2007).

Further, resource managers and scientists recognize the need to move toward ecosystem-based management of fisheries (Browman and Stergiou, 2005; Rosenberg and McLeod, 2005; Sherman et al., 2005; Frid et al., 2006). This provides new impetus to improve our understanding of environmental factors that influence fish stock dynamics and to make environmental variability an integral part of the assessment process. Therefore, routine monitoring of ecosystem parameters such as chlorophyll and marine primary productivity will be increasingly important.

Many spatial features that characterize ecosystems and ecosystem variability—such as ocean fronts, eddies, convergence zones, and river plumes—can be resolved only with satellite data (Holligan et al., 1983b; NRC, 2008a). Moreover, remote sensing of primary productivity and chlorophyll facilitates monitoring the base of the oceanic food chain, which is part of the assessment strategy for large marine ecosystems (Sherman and Hempel, 2008; Chassot et al., 2011; Sherman et al., 2011). For example, satellite chlorophyll data are a key indicator used in the California Current Integrated Ecosystem Assessments (NOAA, 2011).

How to assess the impact of climate change on fisheries?

There is considerable long-term temporal variability in fish stocks. It is a challenge to differentiate the effects of interannual variability and overfishing from long-term changes such as regime shifts (IOCCG, 2008). These regime shifts are characterized by relatively rapid changes in baseline abundances of both exploited and unexploited species (Kendall and Duker, 1998). In addition to SST, changes in chlorophyll can be an index to detect these climate regime shifts early on because these measurements are available from satellites with little time lag and provide basin-scale and global views. To sustain fisheries, management practices need to be flexible enough to recognize and accommodate ecosystem-wide regime shifts (Polovina, 2005).

Long-term changes in ecosystems can be linked to ocean and atmosphere parameters (Mantua et al., 1997; Hare and Mantua, 2000; Peterson and Schwing, 2003). For example, a regional change from a cool to warm climate in the North Pacific in the 1970s coincided with a shift from a shrimp-dominated ecosystem to one dominated by several species of groundfish (Botsford et al., 1997; Anderson and Piatt, 1999). Similar shifts have been observed for many different species and in all ocean basins. Yet the mechanisms that link changes in population abundance to large-scale ocean and atmosphere dynamics are not always clear (Botsford et al., 1997; Baumann, 1998), and the relationships are not always constant (Solow, 2002).

In most cases the relationship between chlorophyll and a specific fish stock is indirect. However, for herbivorous species such as anchovies and sardines, the link can be direct (Ware and Thomson, 2005). Satellite-derived measurements of chlorophyll data provide a fundamental measurement of the base of the oceanic food web that is key to measuring ecosystem changes on a global scale. For example, by extrapolating satellite-derived values of net primary productivity up several trophic levels, Wilson et al. (2009) calculated that the biomass of fish in the ocean are a major but previously unrecognized source of oceanic carbonate that can contribute significantly to the marine inorganic carbon cycle. Satellite measurements of primary productivity also are important for assessing the distribution and diversity of marine organisms (Rosa et al., 2008). In addition, ocean color remote sensing can be used to indirectly extrapolate to benthic habitat or to export production from the base of the euphotic zone (Laws et al., 2000).

Understanding the mechanisms that link changes in fish population to the climate system will require long-term time-series of key ecosystem parameters. Such understanding will be central to developing new management strategies, given the projected long-term climate trends. Modeling studies suggest that climate change will result in a large-scale redis-

[3] Annual recruitment definition: the number of new individuals of a stock that enter the fishery in a given year.

tribution of fisheries' catch potential (Cheung et al., 2008b). The high-latitude regions are projected to experience a 30 to 70 percent increase in catch potential, while a decline of up to 40 percent is projected for low-latitude regions. These major changes will be accompanied by changes in biodiversity (Cheung et al., 2008a).

Global primary production measurements from satellites, together with fish catch statistics and food web models, can be used to estimate the carrying capacity of the world's fisheries (IOCCG, 2008; Chassot et al., 2010). Much of the world's fish catch comes from coastal areas, which are near or beyond their carrying capacity based on recent estimates (Pauly and Christensen, 1995). Ocean color data, therefore, is paramount for managing fisheries over the long term.

How to characterize ocean habitats remotely?

Reflectance of the seafloor holds great promise for characterizing and monitoring shallow benthic habitat from space. In "optically shallow waters," where the reflectance of the seafloor influences the ocean color observed at the sea surface, ocean color is used to characterize bottom types. Ocean color remote sensing offers a cost-effective and repeatable approach for mapping and potentially quantifying benthic substrate. In addition, ocean color can help detect large-scale changes in the health of coastal pelagic and benthic ecosystems, particularly in large homogenous regions (Dekker et al., 2006). Current and planned U.S. research satellites, however, do not provide the required high spatial and spectral resolution for all applications in this class. Many resource managers and other users will likely need a better mix of satellites with superior resolution.

Airborne ocean color sensors have been used to document resilience of benthic features to hurricanes and other large-scale disturbances. Seagrass distributions observed in the eastern portion of the Bahamas Banks near Lee Stocking Island using high-resolution imagery from the Portable Hyperspectral Imager for Low Light Spectroscopy (PHYLLS) were analyzed. Meadows varied from sparse to dense over meter scales (Dierssen et al., 2003). Although Hurricane Floyd inflicted significant damage to structures on the adjacent island, ocean color data revealed that turtlegrass distributions in the region were virtually undisturbed. Satellite observations from Landsat and other multispectral imagers have been used to determine the space-time distribution of Giant Kelp biomass in California and its relationship to nutrient availability and surface wave disturbance (Cavanaugh et al., 2011).

In addition, ocean color imagery can easily identify turbidity or sediment re-suspension events, often caused by storms or high winds, because of the high backscattering signals of the suspended sediments (Acker et al., 2004; Chen et al., 2007; Hu and Müller-Karger, 2007; Dierssen et al., 2009). For example, after the passage of Hurricane Dennis in July 2005, substantial sediment re-suspension covered nearly the entire west Florida shelf. Such turbidity events can affect seagrasses or corals in two ways: these events can be associated with potential eutrophication, which can lead to hypoxic conditions that increase benthic mortality, and increases in water column turbidity that reduces available light for photosynthesis (Adjeroud et al., 2002; Zimmerman, 2006).

How to manage protected species?

NOAA's Office of Protected Resources manages approximately 300 species, including those listed under the Endangered Species Act and the Marine Mammal Protection Act. The Endangered Species Act requires NOAA to designate "critical habitat" and to develop and implement recovery plans for threatened and endangered species. As the only satellite measurement of the marine ecosystem, ocean color data are a crucial tool for characterizing the habitat and behavior of protected species. The Transition Zone Chlorophyll Front (TZCF), which migrates seasonally between 30°N and 40°N in the North Pacific, is an important foraging and migration corridor for a number of marine species (Polovina et al., 2001, 2004), including the endangered monk seal. The interannual variability of the TZCF also affects the ecosystem as far south as the northern atolls of the Hawaiian Archipelago—the Kure, Midway, and Laysan Atolls. In some years, the TZCF remains north of those atolls all year. In other years, the TZCF shifts far enough south during winter to infuse the atolls with higher-chlorophyll water, making the region more biologically productive. This variability has been observed to affect the population of the monk seal. After a winter during which the TZCF shifted south, monk seal pup survival increased (Baker et al., 2007).

Ocean color data also have been used to help with the management of the North Atlantic Right Whale, one of the most endangered whale populations with fewer than 400 individuals left (International Whaling Commission, 1998; Kraus et al., 2005). High mortality, especially as a result of ship strikes and whales becoming entangled in fishing gear, limits the recovery of this population. Because whale habitat overlaps with lucrative fishing grounds and shipping lanes of major U.S. ports, reducing mortality is politically and economically challenging (International Whaling Commission, 1998; Kraus et al., 2005). The current management strategy limits adverse impacts by requiring modifications of fishing gear or vessel speeds in regions where and during times when whales are likely to be present. Satellite ocean color data have been used to identify whale feeding grounds. For example, an effort to provide managers with a forecast of right whale distributions has the goal of avoiding whale strikes by merchant ships (Pershing et al., 2009a,b).

Lastly, satellite ocean color data are crucial in biologging studies, in which animals are tagged to obtain measurements as they move undisturbed through their environments. Recent advances in biologging technology have advanced our understanding of the ecology of top predators and have permitted observations previously unavailable from standard measurement techniques (Bograd et al., 2010). Satellite data make it possible to place the tagging data in an environmental context so that we can understand the foraging and migration patterns. This approach has been used to characterize the behavior and habitat of a wide variety of tagged species, including turtles, penguins, seals, salmon, whales, and sea birds (Hinke et al., 2005; Ream et al., 2005; Polovina et al., 2006; Weng et al., 2007; Block et al., 2011).

Near-Real Time Applications for Ocean Color Products

Applications for ocean color products that require near-real time (NRT) turnaround, from image acquisition until final products reach users, present significant challenges. The best possible analysis must be done with whatever imagery is available at a given moment, which often is not the best imagery for the task. GEO satellites are ideal for collecting NRT data, but the only ocean color geostationary satellite is the Korean Communications Oceanography and Meteorology Satellite (COMS) that currently provides data over the Korean Pacific Ocean. Other approaches are possible; Appendix D describes one cost-effective option to obtain GEO ocean color data.

Military Applications

Much U.S. Navy-sponsored research in the past 10 to 15 years has been directed at coastal and optically shallow waters. The main goal is to characterize the optical properties of the environment for operation of ships, submarines, and divers in the water. A major thrust of the research has been to develop and test airborne hyperspectral sensors and algorithms for mapping bathymetry and bottom type at meter spatial scales in optically shallow waters.[4] Recent projects funded by the Office of Naval Research that investigate these and related topics include Coastal Benthic Optical Properties (1997 to 2002) and Hyperspectral Coastal Ocean Dynamics Experiment (1999 to 2004). Other countries, especially Australia and the People's Republic of China, have invested heavily in the development of airborne hyperspectral imagery capabilities for their coastal waters.

The Navy also uses ocean color to determine water clarity, in order to decide whether particular sensors (such as mine-finding or bathymetric LIght Detection and Ranging sensors [LIDAR]) can be deployed or visibility is adequate for diver operations. The military uses surface measurements of ocean color products to initialize or validate physical-biological ecosystem models, which permit the extrapolation to greater depth of properties such as chlorophyll, absorption, and backscatter that affect visibility and mixed-layer thermodynamics.

Monitoring of Oil Spills

The Oil Spill Response Research Program in the U.S. Department of the Interior pursues techniques for early detection, containment, and clean up of oil spills. Remote sensing can be used to detect spills because the oil changes surface reflectance properties and the color of the ocean. Application of MODIS 250-m imagery can help locate natural oil seeps and improve estimates of natural oil seep rates in the ocean because of the near-daily revisit and wide sun-glint coverage (sensors are usually designed to avoid sun glint, which interferes with obtaining good chlorophyll data, but sun glint is particularly effective at capturing the presence of oil at the surface; Hu et al., 2009). In addition, data from both the MODIS and MERIS sensors were used to track the massive Deep Water Horizon oil spill in the Gulf of Mexico in spring and summer 2010. Surface manifestation of oiled water within the region of sun glint in the full resolution "true color" images was readily apparent. Scientists mapped the extent of the spill and the location of areas of convergence in order to direct ship activities focused on rescuing oiled turtles (Dave Foley, personal communication).

Airborne Visible InfraRed Imaging Spectrometer (AVIRIS) provides full solar spectral reflectance observations that were used during the Deepwater Horizon event to determine the spatial distribution of oil layer thickness. These observations are useful in routine oil spill monitoring and response efforts to differentiate recoverable oil films (> 0.1 mm) from thinner films. The use of multispectral UV-visible detectors, coupled to thermal infrared detectors, allows detection and discrimination of oil films. During spill events, decision makers need access to imagery within two hours of data collection.

However, current satellites are limited in their capacity to assist in oil spill detection. Coarse spatial and temporal resolution, limited spectral bands, cloud-cover issues and the need to operate in conditions of high sunlight have generally restricted the usefulness of ocean color data from low Earth orbit satellites for oil-spill detection (Fingas and Brown, 1997, 2000; Hu et al., 2003). Moreover, current processing methods may not allow for data availability within two hours of data capture. The AVIRIS sampling covered only a small part of the Gulf of Mexico region.

The spatial, temporal, and spectral resolution needed for oil spill recovery planning requires high resolution, hyperspectral ocean color radiometers deployed in geostationary orbit. Geostationary sensors can scan large regions of the ocean over long periods—a clear advantage over airborne sensors. This reduces problems with cloud cover, and the wide coverage can help optimize the deployment of airborne and marine assets. Plans for the proposed hyperspectral ocean color sensor on Geostationary Coastal and Air Pollu-

[4] Shallow waters are defined as waters where bottom reflectance significantly affects the water-leaving radiance. Depending on inherent optical properties of the water, this depth ranges from less than one to tens of meters.

tion Events mission (GEOCAPE; a decadal survey mission; [NRC, 2007]) call for a spatial resolution of about 300 m and the operational flexibility to observe special events, such as oil spills. In addition, Appendix D describes a cost-effective means to provide ocean color data from commercial GEO satellites, to be demonstrated in fall 2011 by the Commercially Hosted Infrared Payload (CHIRP) program.

Detection and Early Warning of Harmful Algal Blooms

Ocean color products are an important component in forecasting HABs, which requires frequent observations over a large area to assess bloom location and movements (IOCCG, 2008). HABs can sicken or kill animals and humans by degrading the water quality or by producing algal toxins, which harm by direct exposure or through consumption of contaminated food.

For example, some HAB species cause areas of extremely low-oxygen water, which can kill a large portion of the sessile fauna (Rabalais et al., 2001). Other HAB species have caused large kills of birds and marine mammals along the U.S. West Coast (Trainer et al., 2000). To avoid human deaths, such as in eastern Canada in 1987 (Subba Rao et al., 1988; Bates et al., 1989; Wright et al., 1989), fisheries are closed in affected areas, and their closure is associated with a loss in revenue. Toxins released to the atmosphere by *Karenia brevis* blooms have been linked to respiratory illnesses along the Gulf of Mexico coast (Hoagland et al., 2009).

HAB events adversely affect commercial and recreational fishing, tourism, and valued habitats. Advanced warnings of HABs and estimations of their spatial distributions increase the options for managing these events, avoiding exposure of humans to the toxins, and minimizing the negative effects on local economies and the livelihood of coastal residents.

Various methods are being developed to improve the detection of HABs with ocean color sensors (Stumpf et al., 2003; Hu et al., 2005; Tomlinson et al., 2009; Zhao et al., 2010). However, many challenges remain. In particular, the spatial and spectral resolution of current ocean color sensors can be too coarse to detect features in many coastal regions. In the case of some harmful algal blooms, there may not be any feature among their optical properties that can be used to distinguish them from non-toxic blooms (Sathyendranath et al., 1997). Despite the limitations, satellite ocean color can be an effective tool for monitoring HABs, which NOAA has done in the United States since 2006, producing HAB bulletins twice a week for the Gulf of Mexico (Stumpf et al., 2009). Efforts also are under way to develop ocean color-based operational HAB forecasts in Europe (Johannessen et al., 2006) and Australia (Roelfsema et al., 2006). Recently methods have been developed for predicting domoic acid-producing *Pseudonitschia* blooms that use satellite ocean color and regional ocean circulation model data products (Anderson et al., 2011). As with monitoring for oil spills, geostationary ocean color satellites (Appendix D) would be invaluable assets for monitoring HABs because they provide the required frequency and spatial resolution to be effective.

Locating Productive Fishing Areas

As fish stocks dwindle, the fishing industry increasingly relies on technology to locate and catch fish quickly and at less cost. Satellite maps of sea surface temperature and ocean color can help increase efficiency by identifying sites of fish aggregation and migration, such as temperature fronts, meanders, eddies, rings, and upwelling areas (Laurs et al., 1984; Fiedler and Bernard, 1987; Chen et al., 2005). In addition, ocean color or temperature gradients can be used to indicate biologically productive regions. Fishermen with knowledge of particular fish species' temperature ranges and preferences have been using SST from the NOAA polar orbiting satellite for the past 20 years.

However, for ocean color to be of practical use to the fishing industry on a large scale, remotely sensed chlorophyll maps must be made available in near-real time. In Japan and India the national fisheries agencies use ocean color to increase the efficiency of their fishing fleets. For example, data from the Indian Ocean color satellite is used to provide maps of potential fishing zones in NRT (Nayak et al., 2010). In contrast, NMFS does not distribute "fish-finding maps" or provide other services that would compete with commercial interests. Chlorophyll data from the privately owned SeaWiFS satellite were only available on a real-time basis to commercial subscribers. Only clients of the service company can receive custom-tailored maps of ocean color and other satellite-derived data directly onboard their fishing vessels.

Identifying Areas with Potential for Marine Debris Convergence

Marine debris and abandoned fishing nets, also called "ghost nets," pose a serious hazard to many marine mammals and sea birds (Jacobsen et al., 2010). Endangered sea turtles, seals, and whales are among the species that become entangled in the nets and die. The nets become ensnared on coral reefs and damage the reef structure, destroy flora and fauna that depend on a healthy reef ecosystem (Donohue et al., 2001), and can harm commercial fisheries (Kaiser et al., 1996; Gilardi et al., 2010).

Satellite ocean color data are part of the methods being developed to identify and prioritize the likely locations of marine debris in order to remove it from the ocean. In one instance, satellite ocean color data were used in the subtropical North Pacific to detect probable locations of debris convergence. A field program validated the detection method (Pichel et al., 2007). Satellite measurements of chlorophyll and the chlorophyll gradient were analyzed in conjunction with observer sightings to generate a map of the likelihood and density of debris. Ocean color data were vital to this identification method; initial efforts using only satellite temperature data were much less effective.

Cruise Support

Near-real time satellite data are invaluable for guiding oceanographic research and operational fishery survey cruises and are used in this manner by NOAA, the Coast Guard, and the research community. The Warm Core Rings experiment in the early 1980s, using the Coastal Zone Scanner (Brown et al., 1985), demonstrated the utility of NRT ocean color data for guiding oceanographic expeditions. NRT data are important for locating blooms, fronts, eddies, and other relevant features for sampling or process studies. The spatial coverage provided by satellite data is crucial for placing ship-based observations in a larger geographic context.

Future Applications

Chapter 5 describes how future enhancements could increase the value of ocean color products. Advances in satellite sensor technology, increased spectral and spatial resolution, and the addition of sensors in geostationary orbits that would allow frequent sampling and even greater spatial resolution would expand the value of ocean color products to climate scientists, the ocean research community and the military, among others (NASA, 2006). Such advances would allow better characterization of coastal environments from space, including the benthic and estuarine environments. LIDAR sensors would expand ocean color observations to greater depths, dramatically enhancing the accuracy of global plant biomass and carbon estimates. Lastly, the Navy is eager to obtain higher spatial and temporal resolution in shallow coastal waters, available from GEO (Appendix D), and would benefit from the vertical resolution provided by LIDAR sensors.

OCEAN COLOR DATA SPECIFICATIONS IN SUPPORT OF OCEAN COLOR APPLICATIONS

As the user community broadens, ocean color product requirements grow increasingly diverse. For example, global biogeochemical modeling studies require global images of relatively coarse spatial resolution, whereas HAB work requires frequent, high-resolution observations only available from GEO (Appendix D).

There are three primary product characteristics for applications of ocean color data: spatial resolution, wavelength resolution, and repeat time. Spatial resolution refers to the area of the ocean surface that corresponds to a single image pixel (i.e., ground sample distance). This can range from less than 1×1 m to more than 1×1 km. Wavelength resolution refers to the number of wavelengths measured and their bandwidths. It can vary from monochromatic (a gray scale with perhaps all visible wavelengths sensed) to multispectral (typically 5-15 wavelengths with each band 10-20 nm wide), to hyperspectral (~30 to a few hundred wavelengths with bandwidths of 10 nm or better). Repeat time refers to the time between successive images of a given location on Earth. It varies from multiple images per day, available only from GEO satellites, to several days for satellites in polar orbit, or on a monthly or less frequent basis (especially in areas with frequent clouds).

TABLE 2.1 Four Types of Satellite Sensors Required to Meet the Observational Needs

Type	Description	Examples
1	Polar orbiting sensors with relatively low spatial resolution (1 km) with 8 (or many more) wave bands.	SeaWiFS, MODIS, VIIRS, PACE/ACE
2	Polar orbiting sensors with medium spatial resolution (250-300 m) and more bands to provide a global synoptic view at the same time as allowing for better performance in coastal waters (but with longer repeat times for global coverage).	MERIS, OCM-1, OCM-2
3	Hyper-spectral sensors with high spatial resolution (~30-100 m) in polar orbit and even longer repeat times.	HyspIRI
4	Hyper- or multi-spectral sensors with high spatial resolution in geostationary orbit.	GOCI, GOCI-II, GEOCAPE

While a polar orbiting satellite sensor like SeaWiFS can deliver a global image about every three days, it cannot increase its spatial or temporal resolution to respond to requirements for higher resolution during an event such as an oil spill. In such a case, a geostationary satellite (Appendix D) that could increase its sampling frequency for a given location would be ideal. The committee identified four general types of sensors to cover the spectrum of observational needs (Table 2.1).

The required data specifications were determined for each application of ocean color data described in this chapter (Table 2.2).

As Table 2.1 illustrates, the needs of the research and operational community are too diverse to be met by a single satellite. For example, a sensor in polar orbit designed to provide global synoptic coverage will not be able to provide the high spatial and temporal resolution required to meet the operational needs of the military or to be of use during an oil spill response.

TABLE 2.2 Current Applications of Ocean Color Data and Required Data Specifications

Application	Spatial Resolution[a]	Wavelength Resolution	Repeat Time[b]	Coverage	Sensor Type	References
Research and Societal Applications:						
Chlorophyll variability and trends at regional to global scales	1 km	Multispectral	2-3 days	Global	1	Many
Trends and variability in carbon fixation at regional to global scales	1 km	Multispectral	2-3 days	Global	1 or 2	Many
Measure inherent optical properties	1 km	Multispectral	2-3 days	Global	1	IOCCG, 2006
Phytoplankton physiology; C:chl ratios; physiological states and growth rates	1 km	Multispectral including fluorescence wave band	2-3 days	Global	1	Behrenfeld et al., 2005, 2009 Sathyendranath et al., 2009
Phytoplankton phenology; Time-series of chlorophyll, primary production, phytoplankton functional types	4-10 km for open ocean; better for coastal waters		Week-monthly	Global	1	Platt and Sathyendranath, 2008 Siegel et al., 2002
Carbon inventory of the ocean (colored dissolved organic matter, particulate carbon, particulate inorganic carbon, phytoplankton carbon)	4-10 km for open ocean; better for coastal waters	Often derived from chlorophyll and IOPs	Week-monthly	Global	1, 2 or 4 depending on application	Balch et al., 2005 Behrenfeld et al., 2005 Gordon et al., 2001 Siegel et al., 2002
Climate change impacts on ocean ecosystem	1 km	Multispectral	2-3 days	Global	1	Henson et al., 2010
Detection of phytoplankton functional groups	1 km	Multispectral, selected narrow bands; sometimes derived from IOPs or chlorophyll	Weekly	Global	1 and 2	Bracher et al., 2009 Sathyendranath et al., 2004 Alvain et al., 2005 Nair et al., 2008
Heat budget and upper ocean dynamics; air-sea interactions (Diffuse attenuation coefficient for visible solar energy)	1 km or better	Multispectral	1 day	Global	1	Many papers; e.g., Gnanadesikan et al., 2010 Murtugudde et al., 2002 Ohlmann et al., 1996 Sathyendranath et al., 1991
Fisheries and Ecosystem Based Management:						
Ecosystem Based Management (Fisheries)	1 km	Multispectral	2-3 days	Global	1	
Mapping the boundaries of ecological provinces in the ocean and their movement	4-10 km for open ocean; better for coastal applications	Derived from chlorophyll, SST and other satellite-derived products	Various time scales of interest, from 1 week to 1 year	Global	1	IOCCG Report No. 8, 2009
Coastal dynamics (suspended sediment load, sediment transport, river plumes, etc.)	100 m to 1 km	Multispectral	Hourly to 3 days depending on region and need;	Coastal and estuarine waters	1, 2, 3, or 4	Many papers (e.g., Warrick et al., 2004)

TABLE 2.2 Continued

Application	Spatial Resolution[a]	Wavelength Resolution	Repeat Time[b]	Coverage	Sensor Type	References
Monitor coral reefs	10 m best, 50 m OK for mapping entire reef systems	Multispectral	Annual	Coastal, 30 N to 30 S, so Geostationary OK	3	Hochberg, 2011 Lubin et al., 2001
Monitor sea grass beds and kelp forests and biomass	3-30 m for biomass (100 m for mapping)	Multispectral	Twice a year	Coastal and estuarine, 60 N to 60 S	3	Cavanaugh et al., 2011 Hill and Zimmerman, 2010
Near-Real Time Applications:						
Naval application for shallow water bathymetry and bottom classification	1-10 m	Hyperspectral best, multispectral is still useful	On demand	Coastal waters, as needed	1-4	Dekker et al., in press Mobley et al., 2005
Monitoring oil spills	100 m	Multispectral	Hourly	Episodic regional events	4	Hu et al., 2009
Detection of HABs	100 m to 1 km	Multi, but hyper better	1 day to monitor blooms	Coastal and estuarine waters	1 and 2	Ruddick et al., 2008

[a] Minimum to sustain current capabilities, not necessarily optimal.
[b] Equatorial revisit.

CONCLUSION

The extensive list of research and societal applications presented in this chapter demonstrates that ocean color is fundamental to and irreplaceable for a wide array of applications at local to global spatial scales and near-real time to decadal time scales.

Exploring the full potential of ocean color research will require more than sustaining current efforts including major advances in sensor capabilities, atmospheric corrections, and algorithm and product development as further described in Chapter 5. Ocean color has been recognized as an essential climate variable[5] by Global Climate Observing System[6] (GCOS). To detect long-term climate trends in marine phytoplankton abundance, long time-series of sufficient quality are required, making it imperative that we maintain and advance satellite capabilities. With the anticipated impacts of climate change on the marine ecosystem, monitoring the changes will be essential to managing the diminishing resources in the ocean.

Further, the expanding use of ocean color products in research and resource management demands a range of spatial and temporal product specifications that are beyond the ability of a single satellite mission to deliver (see Chapters 4 and 5 for details). Wavelength resolution requirements range from only a few bands (to determine chlorophyll) to hyperspectral data (for coastal and naval applications as well as for advanced algorithms for atmospheric correction and the separation of phytoplankton absorption from CDOM; see Chapter 3). A polar orbiting satellite can provide a global image about every three days at relative coarse spatial resolution and meet requirements for applications that need a global synoptic view, such as climate research. The same satellite, however, cannot deliver multiple images per day at the high spatial resolution required by the Navy or by an oil spill response. Those scenarios require a GEO satellite (Appendix D).

Conclusion: A mix of orbits and sensors are required to meet the indisputable demand for a continuous ocean color record that will help us to understand changes in the global climate system, assess the health of the marine ecosystem, and sustain important fisheries, among other crucial societal tasks.

[5] See http://www.wmo.int/pages/prog/gcos/index.php?name=EssentialClimateVariables; accessed June 10, 2010.
[6] See http://www.wmo.int/pages/prog/gcos/Publications/gcos-138.pdf.

3

Lessons Learned from Ocean Color Satellite Missions and Essential Requirements for Future Success

Building and launching a sensor are only the first steps toward successfully producing ocean color radiance and ocean color products. Even if the sensor meets all high-quality requirements, without stability monitoring, vicarious calibration, and reprocessing capabilities, the data will not meet standards for scientific and climate-impact assessments. This chapter surveys lessons from previous missions and outlines the requirements for obtaining useful ocean color data from a global remote sensing mission.

During the past three decades, several polar orbiting satellites have been launched to measure water-leaving radiance (L_w) on a global scale approximately every one to three days (depending primarily on swath width; see Appendix A for a detailed satellite description). The progression from the Coastal Zone Color Scanner (CZCS) to the Sea-viewing Wide Field-of-view Sensor (SeaWiFS), to the Moderate Resolution Imaging Spectroradiometer (MODIS), and finally to the Joint Polar Satellite System (JPSS) Visible Infrared Imager Radiometer Suite (VIIRS), represents the progression from pilot study to research to operational ocean color remote sensing for the United States. With the exception of the most recent European Medium-Resolution Imaging Spectrometer (MERIS) mission, each of these satellite missions carried a Type 1 (see Table 2.1) sensor with only moderate spatial and spectral resolution. The planned Pre-Aerosol-Clouds-Ecosystem (PACE) mission outlined in the National Aeronautics and Space Administration's (NASA) Climate Architecture Plan (2010) represents an advanced Type 1 ocean color research mission. Therefore, this retrospective analysis is restricted to Type 1 sensors. Although some conclusions and recommendations are specific to Type 1 missions, many lessons about mission design and requirements apply to all sensor types.

THE COASTAL ZONE COLOR SCANNER: PROOF OF CONCEPT

CZCS was the first ocean color sensor to provide local- to global-scale ocean color observations during its operation from 1978 to 1986 (Hovis et al., 1980; Gordon and Morel, 1983). CZCS was launched on Nimbus 7 and was a prototype mission to demonstrate that ocean color can be retrieved from space. Therefore, CZCS did not routinely or continuously collect global data because it had to share power and tape recorder capacity with other sensors.

The quality of CZCS data products was significantly compromised by the lack of a sustained in situ monitoring program of L_w to provide sea-truth for the satellite measurements, and by the lack of near-infrared wavebands for atmospheric correction (Evans and Gordon, 1994). During the initial phase of CZCS, NASA and the Nimbus Experiment Team supported a well-formulated program of in situ observations. These data were key in providing the initial instrument vicarious calibration; however, the program was active only during the first months of CZCS on-orbit lifetime (Werdell et al., 2007). Because CZCS experienced significant degradation of the green and blue bands over its lifetime, and the red band used for atmospheric correction experienced an abrupt shift in its performance, CZCS calibration relied heavily on clear water assumptions for the green bands and other simplifying assumptions that could not be validated (Evans and Gordon, 1994). Further, sampling by CZCS was not global and except for regions where data were routinely collected such as the coastal United States, special requests were necessary to initiate data acquisition. In fact, no CZCS observations were ever made in large regions of the global ocean, such as in the South Pacific Subtropical Gyre. Limitations in sensor performance and the lack of sustained, continuous global observations restricted CZCS's ability to quantify long-term changes in the global ocean biosphere. However, the need for continuous vicarious calibration was recognized and led to the Marine Optical Buoy (MOBY) system.

Conclusion: During the CZCS era, scientists learned about the importance of continuous sampling to achieve global coverage, of making in situ measurements throughout a mission's lifetime to assess changes in the sensor's gain over time and to validate the data products, and of atmospheric corrections. In particular, the need for near-infrared (NIR) measurements to improve atmospheric correction was recognized during the CZCS experience and led to the SeaWiFS band-set.

LESSONS FROM THE SEAWIFS/MODIS ERA

SeaWiFS and MODIS-Aqua have been highly successful, global-scale U.S. ocean color missions that contributed to major advances in the ocean sciences (Siegel et al., 2004; NRC, 2008a; McClain, 2009). SeaWiFS launched in September 1997 with a design life of five years and operated for 13 years, until December 14, 2010 (Hooker et al., 1992; McClain, 2009). SeaWiFS provided almost daily global Earth coverage from a polar orbit. Six visible bands detected changes in ocean properties with high signal-to-noise ratio (SNR) to allow discrimination of low ocean reflectance against a very high atmospheric background signal. Two near-infrared (NIR) bands were used to estimate aerosol properties for atmospheric correction (although reduction in digitization of the NIR channels was an important source of noise in open ocean retrievals [Hu et al., 2004]). Key design features minimized polarization sensitivity and far-field stray light and enabled the measurement of low signal ocean radiances, and land and cloud reflectance at very high signals, without saturation. A solar diffuser assisted with the on-orbit sensor performance evaluation (Eplee et al., 2007). The sensor tilt capability minimized sun glint. Most importantly, the lunar calibration capability (Barnes et al., 2004) helped SeaWiFS achieve superb long-term stability.

The overall uncertainty level for SeaWiFS calibration gains can be estimated to be ~0.3 percent (assuming independence among the three sources of uncertainty). Reducing the system calibration uncertainty to such a low number was a major accomplishment of the SeaWiFS mission and resulted from a commitment to minimizing the sources of uncertainty from three primary independent sources: (1) uncertainty in the calibration trends in time, (2) uncertainty in the MOBY calibration and its determinations of water-leaving radiance, and (3) uncertainty in the estimation of SeaWiFS calibration gain corrections. The details of the three sources of uncertainty are presented below; however, their contribution to estimation of the overall uncertainty levels are briefly discussed here. First, uncertainty in the estimation of SeaWiFS calibration over time, i.e., sensor sensitivity degradation, has been determined for SeaWiFS using its monthly lunar viewing of the moon at the same phase (Eplee et al., 2004, 2011). Relative calibration coefficients for some bands had decreased by as much as nearly 20 percent (Figure 3.4); however, uncertainty about the fit trend lines for the lunar views were quite small (~0.1 percent for all bands). Second, uncertainties in the MOBY water-leaving radiances ($L_w(\lambda)$) involve both the MOBY spectrometer calibration and the propagation of the subsurface radiances through the water column and the air-sea interface. Brown et al. (2007) provide the contribution of each to the $L_w(\lambda)$ error budget, with the total uncertainty in $L_w(\lambda)$ ranging from 2.1 to 3.3 percent depending on the spectral band. The $L_w(\lambda)$ contribution to the top of the atmosphere radiance is typically 10 percent for oligotrophic waters and clear atmospheres, which are typically found where MOBY has been deployed. Thus the $L_w(\lambda)$ uncertainty is equivalent to 0.21 to 0.33 percent at the top of the atmosphere. Third, uncertainties in the vicarious calibration of gain factors for individual time points were often large (~1 percent; Franz et al., 2007) and are primarily due to uncertainty in the atmospheric corrections (Gordon, 1997; Ahmad et al., 2010). After evaluating many (>50) independent estimates, the uncertainty in the mean gains (standard errors about the mean) are ~0.1 percent (Table 1 in Franz et al., 2007). It is interesting to note that the largest source of uncertainty to the SeaWiFS calibration budget is from the vicarious calibration source used.

In December 1999, MODIS followed SeaWiFS on the Earth Observing System (EOS) Terra spacecraft and in May 2002, on EOS Aqua. Each had a design life of five years (Esaias et al., 1998). Both remain operational after 11 and 8 years on-orbit, respectively. MODIS addresses atmosphere, land, and ocean research requirements; the Aqua sensor continues SeaWiFS ocean color capability.

Unfortunately, the Terra MODIS sensor has major limitations in its application of ocean color products because of poor radiometric and polarization stability (Franz et al., 2008). The recent reprocessing of Terra MODIS (January 2011) was only possible because the entire dataset was vicariously calibrated using SeaWiFS observations. These difficulties with Terra MODIS highlight the need for a stable and well-characterized ocean color sensor.

Nine of 36 MODIS spectral bands are within the visible range matching SeaWiFS, with the exception of slight changes in bandpass (see below). The MODIS sensor includes for the first time spectral bands that detect the chlorophyll fluorescence line height from satellite orbit (Letelier and Abbott, 1996; Behrenfeld et al., 2009). Like SeaWiFS, MODIS is able to measure the low-signal radiance from the ocean as well as the high-signal reflectance from land and clouds throughout the visible and near-infrared. Therefore, MODIS provides full atmosphere, land, and ocean spectral and radiometric coverage for a broad range of applications, including ocean color. Moreover, MODIS improves SeaWiFS calibration with a better solar diffuser, a solar diffuser stability monitor to compensate for solar diffuser changes over time, and a spectroradiometric calibration assembly that monitors radiometric, spectral, and geometric image quality. MODIS also offers lunar views around a 54-degree phase angle (partial moon) for stability assessment. MODIS does not provide a tilt capability to reduce sun glint over the orbit, in principle (but not in practice), the two MODIS systems in complementary orbits (am and pm) were hoped to provide ocean color imagery that would avoid sun glint. Difficulties with MODIS on Terra made these plans unrealistic.

To a large extent, success of the SeaWiFS/MODIS era missions can be attributed to the fact that they incorporated a series of important steps, including: pre-flight characterization, on-orbit assessment of sensor stability and gains, a program for vicarious calibration, improvements in the models for atmospheric correction and bio-optical algorithms, the validation of the final products across a wide range of ocean ecosystems, the decision going into the missions that datasets would be reprocessed multiple times as improvements became available, and a commitment and dedication to widely distribute data for science and education (e.g., Acker et al., 2002a; McClain, 2009; Siegel and Franz, 2010).

Conclusion: SeaWiFS/MODIS' success in producing high-quality data is due to the commitment to all critical steps of the mission, including pre-flight characterization, on-orbit assessment of sensor stability and gains, solar and lunar calibration, vicarious calibration, atmospheric correction and bio-optical algorithms, product validation, reprocessing, and widely distributed data for science and education.

It is important to identify each mission's reasons for success and contribution to a long-term dataset of ocean biosphere parameters. Some of these lessons were available to inform the European MERIS mission or were confirmed as a result of the MERIS experience.

LESSONS FROM THE EUROPEAN MERIS MISSION

The European Space Agency's (ESA) MERIS was launched on the Environmental Satellite (ENVISAT) platform in March 2002. The mission initially had a nominal five-year lifetime, which later was extended so that operations will continue until the end of 2013. MERIS was the first medium resolution optical imager dedicated to Earth observation that ESA conceived and launched.

The mission benefited from the experience that the European science community had gained through its engagement with the former CZCS and SeaWiFS missions, including participation on the SeaWiFS science team. The "Expert Support Laboratory" (ESL; i.e., the group of laboratories in charge of designing Level 1 and Level 2 data processing algorithms) and the "MERIS science advisory group" were formed and sufficiently engaged in advance to ensure that the mission, instrument, algorithms design, and implementation were appropriately developed. Because MERIS is a combined ocean color, land, and atmosphere (clouds) mission, a certain degree of compromise on the design of the instrument and mission was required. This included the specification of sensitivity levels for ocean color applications while maintaining a high dynamic range, as is the case in general with the design of combined sensors such as MODIS or VIIRS. Nevertheless, because the ocean color mission was a priority, important ocean color-driven requirements were met. The MERIS instrument was carefully designed and characterized (a joint activity of ESA and the instrument manufacturer). Consequently, there were no unexpected post-launch instrumental problems, and the result was a very stable and within-specification instrument providing high-quality global data. The careful pre-launch characterization played a critical role in the sensor's success. The early experience with MERIS illustrates two important lessons: (1) international collaboration is an important aspect of achieving high-quality missions; and (2) scientific and technical expert groups need to be formed and engaged from the start and maintained so their expertise can be efficiently and rapidly available for new missions.

After launch, two groups were setup: the "MERIS Quality Working Group" and the "MERIS Validation Team," which have continuously monitored the quality of the Level 1 and Level 2 products and introduced significant improvements to the processing algorithms throughout the mission. These groups recognized the importance of supporting users with dedicated and freely available tools (e.g., BEAM) from the beginning of the mission. These tools were made available as open source software, enabling users to work with and exploit MERIS data without the need to develop their own software to read the products. The open source software enabled users to actively participate in the evolution of the software; in fact, users provided many processors at no cost to the broader MERIS community.

However, in spite of its high-quality data, some elements of the MERIS mission have prevented it from becoming as popular in the international ocean color community as the SeaWiFS and MODIS missions. One reason was an initial data policy that was relatively restrictive, combined with the lack of an appropriately designed and dimensioned data distribution system. Another reason was the absence of gridded global Level 3 products. These obstacles were not due to ESA's reluctance to distribute data but were an outgrowth of ESA history. Indeed, it was not the objective of most previous ESA missions to provide global datasets. Users were appropriately served with limited numbers of individual instrument scenes. However, the oceanography community needs global or at least regional- to basin-scale products. This experience demonstrates that data have to be freely distributed and easily accessible in large amounts and in a format that allows at least basin-scale studies, and ideally, global-scale studies. In addition, gridded Level 3 data are essential to ensure the data can be used efficiently in all of applications. These datasets are necessary to immediately demonstrate the success of the mission and to trigger the science community's interest, which in turn encourages the wide use of the data.

Another specific aspect of MERIS was the absence of a vicarious calibration strategy due to ESA's limited experience with ocean color at the start of the mission design. The mission was conceived with a six-month commissioning phase, after which the instrument was supposed to be calibrated for the rest of the mission without need for further intervention. However, validation activities after the launch demonstrated that the data accuracy was not within requirements (Zibordi et al., 2006; Antoine et al., 2008). This discovery led to acknowledgements by ESA teams that an introduction of vicarious calibration was mandatory. Vicarious calibration was therefore part of the third mission reprocessing carried out at the beginning of 2011.

Conclusion: The MERIS experience illustrates the importance of having a vicarious calibration strategy in place before launch and maintained over the mission lifetime. In particular, a calibration strategy needs to include instrumented sites providing high-accuracy field data.

ESSENTIAL REQUIREMENTS FOR SUCCESS

Ocean color remote sensing is challenging, as the experiences with CZCS, SeaWiFS, MODIS, and MERIS have shown. To arrive at sufficiently accurate products requires significant effort and a dedicated group committed to going above and beyond simply collecting satellite images. For example, because the water-leaving radiance is such a small fraction of the total radiance detected by the sensor, the radiometric calibration and stability of the sensor has to be known to unprecedented accuracies, and the calibration and the stability of the sensor has to be assessed on-orbit (i.e., they cannot be assessed with sufficient accuracy before launch). From the start, planning for a successful mission needs to integrate all aspects of the mission (Figure 3.1). Lessons from previous ocean color missions highlight the importance of the steps depicted in Figure 3.1 (pre-launch tests, stability monitoring, vicarious calibration, product and algorithm validation with in situ data, data processing/reprocessing and improved products/algorithms, and mission feedback).

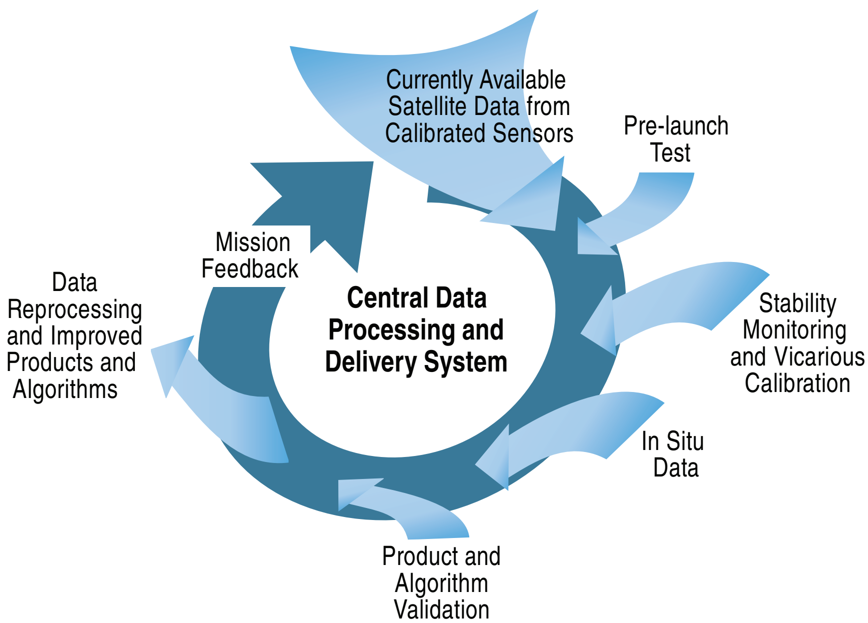


FIGURE 3.1 To improve the derivation and ensure the high quality of water-leaving radiance from multiple satellite sensors a single group needs to be responsible for the following: conduct sensor pre-launch tests, ensure that the sensor's stability is monitored throughout the mission, perform a vicarious calibration, collect in situ data for product and algorithm validation, perform the validation, and routinely process and reprocess the data to improve the products. Once the high-quality water-leaving radiance is produced, users can develop and derive primary and secondary products that satisfy specific requirements of their research or operations. The lessons learned from these steps need to inform and guide current and future missions (adapted from McClain et al., 2002). The ocean color sensor's design needs to include a plan for both pre-launch and on-orbit performance characterization. Furthermore, sequential reprocessing of ocean color data requires both pre-launch characterization of the system, commitments to conduct on-orbit assessments of instrument performance throughout the mission, and support for the necessary research to improve the models used to derive successful ocean color data products. Hence, the requirements for an ocean color mission are multi-faceted and interconnected. Future plans should reflect this integration of requirements.
SOURCE: McClain et al., 2002; NASA's Goddard Space Flight Center.

These and additional requirements for a successful mission are discussed in detail in the following sections.

1. Mission Planning Needs to Include Provisions to Meet All Requirements, Not Just Sensor Requirements

A key lesson from CZCS and SeaWiFS is that a successful ocean color mission requires that the team consider from the beginning all aspects of what it takes to develop high-quality ocean color products. For example, CZCS did not have the required in situ monitoring program to ensure high-quality data throughout the entire mission. Because of the delay in the SeaWiFS launch, additional time was available to build the critical infrastructure, which accounted in large part for the success of the mission. During the SeaWiFS and MODIS era, the requirements were strict for the top of the atmosphere (TOA) radiometric specifications for the satellite mission, and for the algorithms required for quantitative retrieval of ocean chlorophyll. The TOA specifications were designed to achieve a radiometric accuracy of at least 2 percent absolute (without vicarious calibration) and 1 percent relative (band-to-band; after vicarious calibration). The water-leaving radiances (L_w) in the blue band were to have an uncertainty of 5 percent or less, with a relative between-band precision of <5 percent and polarization sensitivity of <2 percent at all angles (Hooker et al., 1992; Hooker and McClain, 2000; McClain et al., 2006; McClain, 2009).

Experiences with SeaWiFS and other ocean color sensors show that, by following prescribed steps that begin with pre-launch sensor characterization and continue throughout the mission, these specifications and other key mission requirements can be met, as is illustrated in Figure 3.1 and in the following sections.

2. Sensor Design Needs to Consider the Calibration and Data Product Requirements When Weighing Engineering Trade-Offs

Sensor designs often attempt to meet the requirements for a diverse set of applications (see Chapter 2). Therefore, sensors vary in spatial resolution, specific spectral band centers, bandwidths, SNR and rated accuracies (see Appendix A), as well as data acquisition and timing. These variations make it challenging to combine data from different sensors to measure trends in ocean biology. Although there have been efforts to define "standard" ocean color sensor characteristics for general applications, establishing common standards may be impractical because sensors for different agencies and nations often serve different applications. However, it is useful to examine lessons from past sensors and the trade-offs of different design choices with regard to how well one can monitor the sensors' behavior and stability pre- and post-launch (Table 3.1). Based on our examination, the committee is able to provide some simple guidelines for a minimal set of high-quality standards that all satellite sensors ideally would adhere to (Figure 3.2). Beyond that, one might also request that certain specifications and "metadata" be available for each sensor, so that researchers can evaluate the applicability of each source of satellite data to a given study topic.

The committee's guidelines for achieving high-quality sensor performance fall into six general areas: Sensor stability, waveband selection, scan geometry, sun glint, sensor saturation, and polarization sensitivity. Explanations and recommendations are as follows:

Sensor Stability

The sensor's stability and monitoring of that stability, is critical, as demonstrated during the SeaWiFS mission. The monitoring approach depends on the sensor design but needs to be an integral part of the overall mission (as discussed below). SeaWiFS also had a solar diffuser, but that data has not been used for temporal trending of the sensor performance because the mission allowed for monthly spacecraft pitch maneuvers to image the moon at a fixed lunar phase angle near full moon. MODIS relies primarily on the solar diffuser data and the diffuser stability monitor. MODIS also views the moon monthly through the deep space port, but at a higher phase angle (partial moon). VIIRS follows the MODIS strategy, but the deep space port is located such that the moon is near the horizon and is not visible most of the year without roll maneuvers (Patt et al., 2005).

Recommendation: Monitoring of the sensor stability should be an integral part of any ocean color mission from the start.

Waveband Selection

For the CZCS pilot study the 670-nm band had to be used for atmospheric correction because the 750-nm band was not sensitive enough for the task. Based on the CZCS experience, additional bands were added to SeaWiFS (see Figure 3.3). SeaWiFS was the first ocean color mission to use NIR bands to enable an atmospheric correction using a detailed inversion procedure (see below). This approach is used with MODIS and will be used for VIIRS.

MODIS also includes additional bands in the visible that can be used to quantify chlorophyll a fluorescence. Chlorophyll a fluorescence is unique in providing information about physiological states and biological activity. MODIS also has land remote sensing bands in the Short Wave Infrared (SWIR) that can be used in atmospheric correction in turbid water conditions (Wang et al., 2009). On MODIS, the 510-nm band (found on SeaWiFS) was replaced with a band centered at 532 nm, but this was found to be too highly correlated with the 555-nm band to be useful in deriving chlorophyll.

VIIRS is missing several key wavebands. It has neither the 510- nor the 532-nm band, which will make it harder to

TABLE 3.1 Key Sensor Characteristics

	CZCS[a]	SeaWiFS[b]	MODIS[c]	MERIS[d]	VIIRS[e]
Operational Dates	Oct. 1978-1986	Sept. 1997-Dec. 2010	Terra Dec. 1999-TBD Aqua March 2002-TBD	March 2002 - TBD	Launch 2012
Ocean Color Wavebands	4 visible	6 visible 2 NIR	7 visible, 2 NIR, & 3 SWIR	9 visible + 6 NIR	5 visible, 2 NIR, & 3 SWIR
Scan	45° angle 360° rotating mirror ±40° scan (1,566 km swath)	360° rotating telescope	360° rotating paddle mirror	Push-broom imager	360° rotating telescope
Sun Glint Avoidance	±20° fore-aft tilt mechanism (2° increments)	±20° fore-aft tilt mechanism (2° increments)	Terra (1,030) Aqua (1,330) comparison	Nadir view; no sun glint avoidance	1,330 (if available) comparisons
Polarization Sensitivity	<3 percent, Scrambler	Scrambler	~5 percent	<2 percent	<2 percent
SNR	100-150	360-1,000	1,250-2,700	>600-1,400	>1,000
Dynamic Range (Sensor Saturation)	Ocean only	Ocean, land, clouds via bi-linear gain control	Ocean only within ocean color bands; other similar cloud/land VNIR bands for bright scenes	Ocean color + land and clouds	Ocean, land, clouds via pixel instantaneous automatic gain control
On-board Calibration	No	No		2 solar diffusers plus an erbium-doped diffuser for spectral calibration	Yes
Monitoring of Stability	No	Yes	Yes	Yes (2 solar diffusers)	Hopefully

[a] CZCS: NASA. 2011. *Ocean Color Web*. [Online]. Available: http://oceancolor.gsfc.nasa.gov/CZCS/czcs_instrument.html [2011, June 7]; Hovis, W.A. et al. 1981. Nimbus 7 coastal ocean color scanner. *Applied Optics* 20:4175.

[b] SeaWiFS: Barnes, R.A. and A.W. Holmes. 1993. Overview of the SeaWiFS ocean sensor. In Sensor Systems for the Early Earth Observing System Platforms, Barnes, W.L. (ed.). *Proceedings SPIE* 1939:224-232; Barnes, R.A., R.E. Eplee, W.D. Robinson, G.M. Schmidt, F.S. Patt, S.W. Bailey, M. Wang, and C.R. McClain 2000. The calibration of SeaWiFS. In *Proceedings of 2000 Conference on Characterization and Radiometric Calibration for Remote Sensing, Logan, Utah, September 19-21, 2000*; Barnes, R.A., R.E. Eplee, Jr., G.M. Schmidt, F.S. Patt, and C.R. McClain. 2001. Calibration of SeaWiFS I. direct techniques, *Applied Optics* 40(36):6682-6700; Eplee, R.E., Jr., W.D. Robinson, S.W. Bailey, D.K. Clark, P.J. Werdell, M. Wang, R.A. Barnes, and C.R. McClain. 2001. Calibration of SeaWiFS. II. Vicarious Techniques. *Applied Optics* 40(36):6701-6718; Hammann, M.G. and J.J. Puschell. SeaWiFS-2: An ocean color data continuity mission to address climate change. In Remote Sensing System Engineering II, Ardanuy, P.E., and J.J. Puschell (eds.). *Proceedings of SPIE* 7458:745804.

[c] MODIS: Guenther, B., W. Barnes, E. Knight, J. Barker, J. Harnden, R. Weber, M. Roberto, G. Godden, H. Montgomery, and P. Abel. 1995. MODIS Calibration: A brief review of the strategy for the at-launch calibration approach. *Journal of Atmospheric and Oceanic Technology* 13:274-285; Schueler, C.F. and W.L. Barnes. 1998. Next-generation MODIS for polar operational environmental satellites. *Journal of Atmospheric and Oceanic Technology* 15:430-439.

[d] MERIS: Curran, P.J. and C.M. Steele. 2005. MERIS: The re-branding of an ocean sensor. *International Journal of Remote Sensing* 26:1781-1798.

[e] VIIRS: Schueler, C.F., P. Ardanuy, P. Kealy, S. Miller, F. DeLuccia, M. Haas, H. Swenson, and S. Cota. 2002. Remote sensing system optimization. *Aerospace Proceedings* 4:1635-1647; Schueler, C.F., J.E. Clement, P. Ardanuy, M.C. Welsch, F. DeLuccia, and H. Swenson. 2002. NPOESS VIIRS sensor design overview. In Earth Observing Systems VI, Barnes, W.L. (ed.). *Proceedings of SPIE* 4483:11-23.

retrieve chlorophyll concentrations in optically turbid waters. It is also missing the chlorophyll fluorescence bands and sensitive SWIR bands. It is critical to have the appropriate bands for the atmospheric correction. SeaWiFS NIR SNRs were too low, whereas those of MODIS and VIIRS are acceptable. SWIR bands are useful in turbid waters; both MODIS and VIIRS SWIR bands have low SNRs (higher SNR is recommended). To retrieve chlorophyll a fluorescence line height (Letelier and Abbott, 1996; Behrenfeld et al., 2009), a narrow (10 nm) band is needed near the fluorescence peak (MODIS uses 678 nm to avoid atmospheric absorption features) and bands on either side of the fluorescence peak (MODIS uses 667 and 748 nm).

One major issue plaguing ocean color imagers is the separation of algal and non-algal absorption coefficients from ocean color signals, especially as the climate changes. Existing methods (Lee et al., 2002; Siegel et al., 2002, 2005a,b; Morel, 2009; Morel and Gentili, 2009) all leverage their

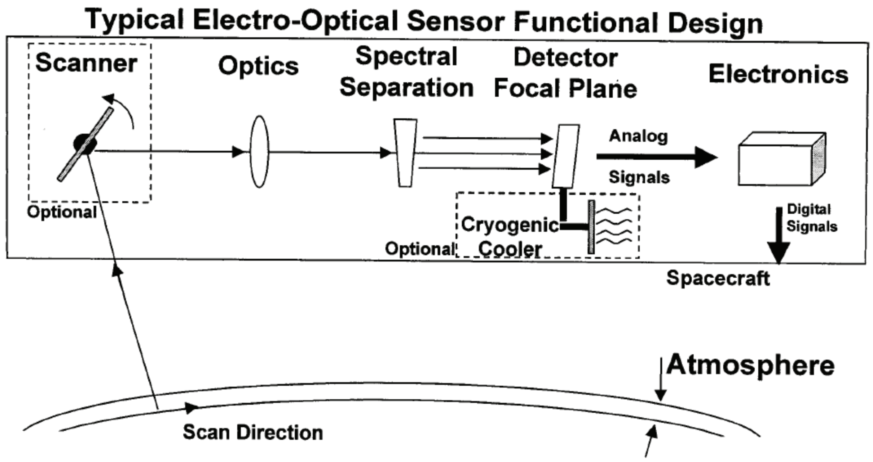


FIGURE 3.2 Ocean color sensor functional elements. This figure uses the example of a scanner to illustrate the fundamental sensor design elements comprising an EOS sensor for ocean color (or other) applications.
SOURCE: Acker et al., 2002a.

success from differentiating the colored dissolved organic matter (CDOM) absorption signal from the algal absorption based on information from a single channel, 412 nm (Lee et al., 2002; Maritorena et al., 2002; Morel and Gentili, 2009). The present operational algorithm for SeaWiFS and MODIS uses four wavelengths to derive chlorophyll concentrations. A single band for discriminating non-algal absorption, such as CDOM, limits the assessment of portioning uncertainty (there is only one degree of freedom). CDOM absorption, the major constituent that needs to be portioned from phytoplankton absorption, increases with shorter wavelengths, and CDOM dominates the absorption spectrum in the near-ultraviolet (UV; Nelson and Siegel, 2002; Nelson et al., 2010). Present plans for PACE and Aerosol-Cloud-Ecosystems (ACE) include wavebands in the near-UV (350, 360, and 385 nm) to better enable this partitioning.[1] Inclusion of several bands in the near-UV would help in separation of algal and non-algal ocean color signals.

Bands in the near-UV likely will be important for improving atmospheric correction procedures. Absorbing aerosols have long confounded existing atmospheric correction methods, as these methods require that aerosol contributions in the visible spectrum can be modeled by knowing NIR aerosol radiance characteristics (Gordon and Wang, 1994a; Gordon, 1997). The presence of absorbing aerosols, generally from land sources (pollution, dust, etc.), makes atmospheric correction models fail under such conditions (Gordon, 1997; Gordon et al., 1997; Moulin et al., 2001). The near-UV provides a path for correcting for absorbing aerosols because the atmospheric signals in the near-UV are much stronger than ocean color signals.[2] With this new information, future atmospheric correction/ocean color algorithms likely will be coupled inversions similar to those trailblazed by Professor Howard Gordon and his students (e.g., Chomko and Gordon, 2001; Chomko et al., 2003).

To ensure continuity of Type 1 ocean color observations, a minimum band-set needs to be maintained on future sensors. The ideal Type 1 sensor would have at minimum the following bands in the visible: 412, 443, 490, 510, 555, 667, 678, and 765 nm, which is a combination of the bands present on SeaWiFS and MODIS (SeaWiFS = 412, 443, 490, 510, 555, 675 nm; MODIS = 412, 443, 490, 531, 555, 667, 678, and 748 nm). As described above, two channels in the near-UV would be useful for partitioning algal and non-algal absorption optical properties and for implementing new algorithms for absorbing aerosols. The ACE science team recommends bands centered on 360 and 385 nm for these purposes; the committee supports this finding. In addition, the sensor would require some SWIR and NIR bands in the atmospheric "windows."

Recommendation: Spectral band-sets for sustaining existing ocean color capabilities should be at least as complete as the SeaWiFS band-set, preferably with improved SNR values, SWIR bands with improved SNR values for atmospheric corrections in turbid waters, the ability to retrieve chlorophyll a fluorescence, and near-UV bands for improving the partitioning of algal and non-algal ocean color signals and for implementing new approaches in atmospheric correction.

[1] ACE 2010 White Paper. Available at: http://www.neptune.gsfc.nasa.gov/.../ACE_ocean_white_paper_appendix_5Mar10.doc.

[2] ACE 2010 White Paper. Available at: http://www.neptune.gsfc.nasa.gov/.../ACE_ocean_white_paper_appendix_5Mar10.doc.

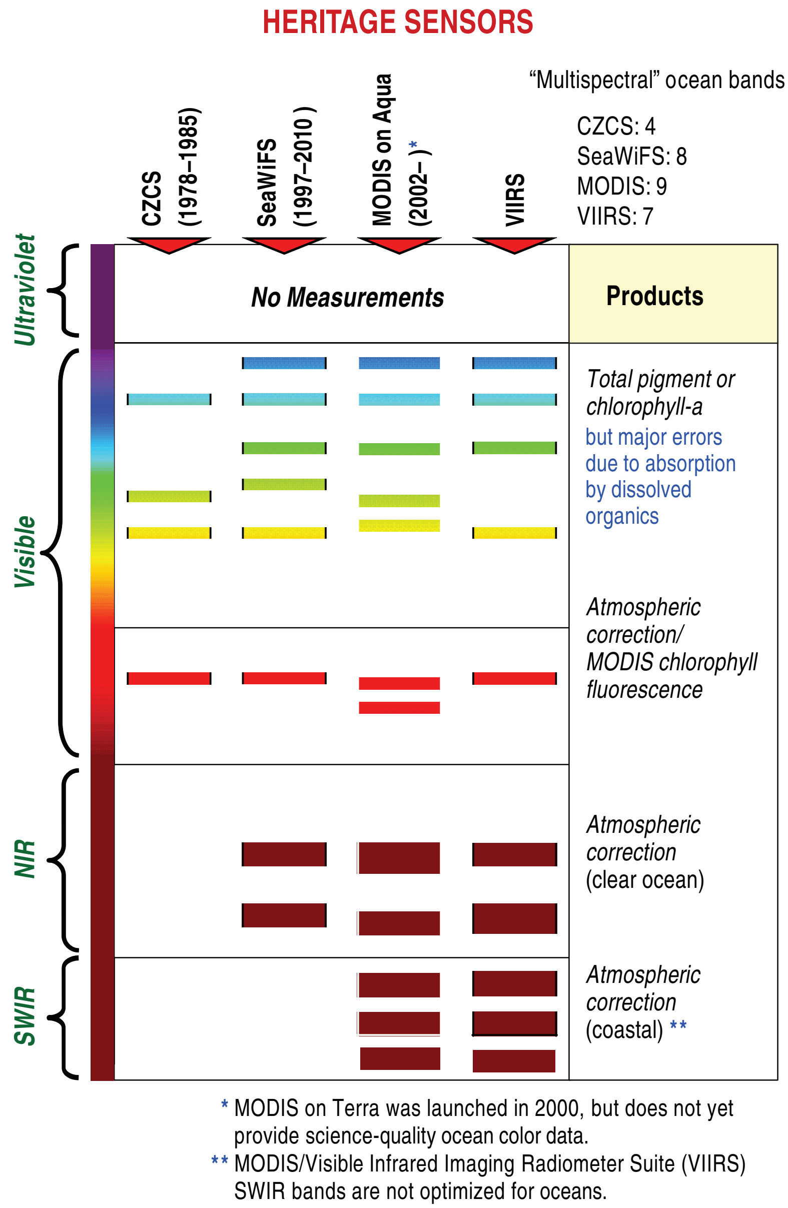


FIGURE 3.3 Comparison of spectral coverage of heritage sensors.
SOURCE: Adapted with permission from Charles McClain, NASA/Goddard Space Flight Center.

Scan Geometry

Sensor scan geometry impacts the reprocessing of ocean color data. SeaWiFS and MODIS reprocessing differ based on their different scan geometry. SeaWiFS used a rotating telescope to provide a cross-track scan, and detectors in one spectral band see different geometry because they are aligned along-scan and read out sequentially as the telescope rotates.

Different spectral bands are displaced along-track (cross-scan), however, so that all bands are read out with the same scan geometry at any Earth location. MODIS uses a cross-track scan mirror. The MODIS detectors in a spectral band are aligned cross-scan (along-track) so that they are read out simultaneously at the same scan mirror position at any Earth location. Different spectral bands on the same MODIS focal plane (e.g., ocean color bands) are read out at different times so that the scan mirror is at a different angle for each band at any Earth location. This affects reflectance and vicarious calibration differently than for SeaWiFS, and complicates the calibration procedures for MODIS compared with SeaWiFS.

Conclusion: When designing a new sensor, it is important to consider how the sensor's design may impact the vicarious calibration and periodic data reprocessing.

Sun Glint

Sun glint comes from the reflection of sunlight from the ocean's surface into the viewing path of the sensor. Retrievals of L_w are nearly impossible for those illumination and viewing angles contaminated by sun glint (Gordon and Wang, 1994b). Existing ocean color algorithms exclude pixels found within the sun-glint pattern (Wang and Bailey, 2001). Sensor and mission design can help mitigate these issues. The CZCS and SeaWiFS sensors were both tilted away from the sun's specular path by 20 degrees to avoid sun glint. MODIS (and VIIRS) is nadir-looking (i.e., without a tilt looking straight down) (Table 4.1). Thus, sun glint contaminates much of MODIS's viewing geometry under high zenith angle conditions such as found in the tropics near noon. This limits the effective spatial coverage by MODIS in the tropical oceans (Gregg et al., 2005; Maritorena et al., 2010). The plans for avoiding sun glint for the two MODIS missions were to use observations from different equatorial crossing times. This approach is problematic as it assumes that MODIS on Terra and Aqua produce similar data streams and that a vicarious calibration for both can still be achieved.

Recommendation: Future ocean color sensors should avoid sun glint by tilting the sensors' viewing away from sun-glint contaminated regions of the oceans.

Sensor Saturation

Avoiding sensor saturation presents a challenge because the signal from clouds and the atmosphere is very high compared with the signal from the ocean. Because most (>90 percent) of the signal detected by the satellite stems from light scattered in the atmosphere, successful ocean color remote sensing depends on correcting for the radiance from the atmosphere. Therefore, measurements of atmospheric signals in both ocean color and aerosol bands are required. Avoiding saturation while also providing sufficient signal sensitivity in the ocean color bands requires either dual simultaneous measurements in each band, or dual-gain, preferably with instantaneous automatic gain control. Dual-gain band offset and gain coefficients differ for each gain. The coefficients are downlinked with the raw data and a flag indicating the gain the detector was in when the measurement was made. Then the offset and gain coefficients are applied to achieve <2 percent radiometric error. Short-term (in the order of a second) detector response instability may cause a small intra-scan, temporally varying, offset and gain coefficient error (affects single- and dual-gain bands). Vicarious calibration is, as shown in Appendix B, insensitive to offset and gain error and therefore insensitive to instability. Therefore, vicarious calibration is applied for ocean color applications to achieve overall levels of radiometric uncertainties of 0.3 percent or less.

SeaWiFS used a bi-linear gain feature that worked adequately for eliminating saturation over all targets, whereas MODIS employs two independent channels in each such band, one at high gain with lower dynamic range for ocean color, and the other with low gain and high dynamic range. VIIRS uses a single dual-gain channel for each band with automatic gain control.

Recommendation: The ocean color sensor design should ensure that saturation can be avoided under any environmental conditions, yet resolve ocean color signals for the effective retrieval of water-leaving radiance spectra.

Polarization Sensitivity

Minimal polarization sensitivity is required. Many of the problems with the processing of MODIS-Terra imagery are related to the time-dependent polarization sensitivity (Franz et al., 2008; Kwiatkowska et al., 2008). Some refinements of the MODIS-Aqua characterization using the same technique were needed in the most recent reprocessing, but the corrections were much smaller than for MODIS Terra. However, use of a polarization descrambler precludes the simultaneous viewing of thermal infrared bands, as is done now in MODIS and VIIRS. Most recently, requirements for polarization sensitivity are <1 percent.

Recommendation: Future ocean color sensors should minimize the polarization sensitivity and residual polarization should be adequately characterized in pre-launch testing.

3. The Sensor Has to Be Well Characterized Prior to Launch

The SeaWiFS and MODIS missions demonstrated the importance of pre-launch sensor characterization because many factors needed for data processing cannot be easily characterized in orbit (McClain et al., 2006). These factors include temperature effects, stray light, optical and electronic cross-talk, band-to-band spatial registration, relative spectral and out-of-band response, signal-to-noise ratios, electronic gain ratios, polarization sensitivity, response versus scan angle, and any instrument specific items, such as selective detector aggregation, that can impact sensor response (McClain et al., 2006). Because it is often impossible to deconvolve sources of error post-launch, these attributes need to be determined prior to launch.

These characteristics vary greatly from sensor to sensor. For example, MODIS, unlike SeaWiFS, has multiple detectors per spectral band and the radiometric and polarization sensitivity is specific to each detector. Measurements of MODIS's polarization sensitivity were questionable and led to a seasonal latitude- and time-dependent error in the retrieved water-leaving radiances (NASA, 2009a). An important part of the characterization process is to allow for free and open discussions between the vendor, representatives of the sponsoring agency and experts from the user community. For both MODIS and SeaWiFS, productive interchanges between vendor, agency, and user community resolved problems prior to launch, and also post-launch as part of reprocessing efforts. These discussions also effectively leveraged the vendor personnel's knowledge of the sensor with the agency personnel's knowledge of algorithm development and cal/val needs.

Because VIIRS was procured as a performance-based contract, it minimized such interactions between vendor and agency personnel. Many initial issues with the VIIRS sensor set to launch on National Polar-orbiting Operational Environmental Satellite System Preparatory Project (NPP) were due to pre-launch characterization results that did not meet specifications. Subsequent testing and end-to-end system testing performed after VIIRS was mated with the NPP spacecraft have shown much better performance characteristics for VIIRS. Some of these discrepancies were due to differences in the test facilities used to test and characterize VIIRS (Turpie, 2010). This demonstrates that test facilities themselves must be adequately designed and tested for the pre-launch characterization of ocean color sensors. Further, International Traffic in Arms Regulations (ITAR)[3] restrictions have prohibited open access to the test program dataset for VIIRS. Such restrictions could seriously compromise the ability of the U.S. community to acquire similar information for foreign sensors. Similar concerns exist about "trade secrets" that would prohibit instrument vendors from openly sharing instrument design information with all affected parties.

Because any ocean color sensor will need repeated vicarious calibrations, the pre-launch absolute radiometric calibration is not as critical, and pre-launch absolute radiometric calibration uncertainties of ~5 percent may be acceptable. This relaxing of requirements would help constrain instrument costs.

Recommendation: An aggressive pre-launch characterization program should be in place for those factors that are not easily adjusted on-orbit with validated test facilities.

Recommendation: Open communication and frequent interactions among the sensor vendor, agency personnel, and the relevant instrument team should be pursued to efficiently leverage knowledge and quickly identify design and algorithm solutions.

[3] The International Traffic in Arms Regulations (ITAR) pertain to export and import of ITAR-controlled defense articles, services, and technologies. It also protects export/import of technology pertaining to satellites and launch vehicles. As a result, some information exchange related to sensor pre-launch and post-launch calibrations could be restricted by ITAR (NRC 2008c: *Space Science and the International Traffic in Arms Regulations: Summary of a Workshop*).

4. Vicarious Calibration Is Required to Achieve On-Orbit Accuracy Goals

Although satellite sensors are calibrated prior to launch, their calibration coefficients likely change during the storage period prior to launch, during the launch, and in orbit while exposed to the hostile space environment. This potential for change requires a post-launch assessment and adjustment of the pre-launch calibration coefficients. The standard and most reliable procedure to achieve such an assessment is a vicarious calibration (Franz et al., 2007; McClain, 2009; see also Appendix B). Vicarious calibration is a process to calibrate a satellite ocean color sensor after launch that begins with high-quality in situ measurements of L_w at the same wavelength band (preferably also accounting for the out-of-band response) as for the satellite sensor. Because the L_w signal reaching a satellite ocean color sensor is small compared to the contribution of backscattered atmospheric radiances, vicarious calibration of satellite ocean color sensors also requires that the L_w signal be accurately propagated via models and calculations from the ocean surface, through the atmosphere and to the satellite sensor. Accurately propagating the L_w signal to satellite altitudes is easier and more accurate at locations where the contribution of the most variable optically active components of the atmosphere (e.g., aerosols) are small, or at worst, sufficiently well-characterized. Thus, the location of vicarious calibration sites is critical. Experience with SeaWiFS and MODIS shows that many observations (at least 50; see also Appendix B) are required before stable and accurate values can be determined for adjusting the calibration coefficients of the satellite sensor (Franz et al., 2007). Because of sunglint contamination, nadir-viewing ocean color missions will take much longer than tilting sensors to achieve a sufficient number of calibration match-ups.

Given the strict accuracy requirements, field instruments used for vicarious calibration have to measure L_w with accuracy on the order of a few percent to implement quantitative algorithms (e.g., McClain et al., 2004). This accuracy is extremely difficult to achieve and requires high-quality in situ instrumentation, accurate models to correct for atmospheric path radiance, and a rigorous process for both acquiring the in situ measurements and for matching the in situ and satellite measurements. This requirement for field observations was achieved for SeaWiFS and MODIS using MOBY (Clark et al., 2002; see Appendix B). MOBY has been extensively characterized using National Institute of Standards and Technology (NIST) resources and is well suited to understand the in-band, out-of-band, and cross-talk responses of the MOBY instrument, permitting proper deconvolution of these signals to obtain the true water-leaving radiance spectrum (Carol Johnson, personal communication; see Appendix B). A dedicated team for developing and maintaining these standard measurements is critical, given the need to maintain strict accuracy over the duration of the satellite mission and beyond (to use these measurements for satellite data inter-calibration).

The approach with MOBY was to develop and implement a robust, rigorous facility to support continuous in situ measurements of water-leaving, spectrally continuous (i.e., hyperspectral) radiances. From hyperspectral measurements, one can synthesize the band-set of any satellite ocean color sensor. The buoy approach was based on the lessons learned from the CZCS mission, during which measurements for the vicarious calibration were performed from ships during the early phase of the mission. MOBY operates 365 days a year, taking measurements three times a day, timed with the overpasses for SeaWiFS and MODIS-Aqua and -Terra. From July 1997 to February 2007, 8,347 measurements were made. However, it is not possible to have a satellite match-up for every MOBY observation (Franz et al., 2007). Clouds obscure satellite views of the ocean. In general, clouds build up during the afternoon, which means the satellite orbital parameters influence the number of useful match-ups. Clouds are one rejection criteria for match-ups between MOBY and satellite sensors; other limiting factors include instrument problems. Of the 8,347 measurements collected during the one-year interval ending in February 2007, about 45 percent of the data were cloud contaminated. About 10 percent were flagged as questionable, and 45 percent were good. During the beginning of the SeaWiFS mission, every possible match-up was utilized (Eplee et al., 2001). As the research of the SeaWiFS calibration continued, the selection criteria were improved and a reduction in the number of match-ups was justified, but it took almost four years to get the 30 match-ups that meet the current criteria. The Ocean Biology Processing Group (OBPG) at NASA's Goddard Space Flight Center (GSFC) excludes data if: 1) the two measures of the water-leaving radiance that are derived from the three different depths using MOBY disagree by more than 5 percent; or 2) the measured surface irradiance differs from a clear-sky irradiance model by more than 10 percent. Satellite sensor datasets are excluded if: (1) there are any flagged (suspicious) pixels in the image; (2) the mean chlorophyll-a concentration retrieved for the scene is greater than 0.2 mg/m^3, which is unusually high for such oligotrophic waters found at the MOBY site; (3) the retrieved aerosol optical thickness in the near-infrared is greater than 0.15 (note this could be an indicator of sun-glint contamination, not actual aerosol contribution); (4) the satellite view angle is greater than 56 degrees; or (5) the solar zenith angle is greater than 70 degrees (Franz et al., 2007). These criteria resulted in only 15 match-ups per year over nine years of MOBY/SeaWiFS continuous operations (Franz et al., 2007).

Franz et al. (2007) conclude that it would take two to three years of continuous in situ operations in order to establish the calibration of an ocean color sensor with characteristics similar to SeaWiFS. However, it should be pointed out that the nature of the SeaWiFS degradation was straightforward to model and to predict, and there were frequent lunar observations at the same phase angle. In general, it cannot be assumed that the degradation is straightforward to model or that frequent match-ups are available due to sun-glint issues. For nadir-viewing ocean color missions such as MODIS and VIIRS, the calibration will take much longer because of sun-glint contamination. The contributions of uncertainties in the MOBY water-leaving radiance ($L_w(\lambda)$) determinations to the vicarious calibration involve both the MOBY spectrometer calibration and the propagation of the subsurface radiances through the water column and the air-sea interface. Brown et al. (2007; Table 5) showed that the total uncertainty in MOBY determinations of $L_w(\lambda)$ under excellent conditions ranged from 2.1 to 3.3 percent depending on the spectral band. The $L_w(\lambda)$ contribution to the top of the atmosphere radiance is typically 10 percent for oligotrophic waters and clear atmospheres, which are typically found where MOBY has been deployed. Thus, the $L_w(\lambda)$ uncertainty to TOA radiance is equivalent to 0.21 to 0.33 percent at the top of the atmosphere, the major source of uncertainty to the SeaWiFS overall uncertainty budget.

Based on lessons learned from SeaWiFS, MODIS, and other sensors, vicarious calibration has to meet certain criteria. The site needs to be in oligotrophic waters but accessible without excessive ship costs. Islands are the logical choice but clouds form around islands—for example, on the windward side of Hawaii, with its high mountain ranges. The leeward side is a better option. The site requires extensive characterization, including optical, biophysical, and biogeochemical, and this requires experienced researchers and ship time to measure, for example, the bi-directional reflectance distribution function. The ideal site would provide a nearby facility for maintenance and related functions including: refurbishment, in-field servicing, improvement of the hardware of the optical buoy and the mooring buoy, radiometric characterization, and pre- and post-deployment calibration for the in situ instrument. In addition, data analysis and data archiving are critical aspects of the vicarious calibration facility operations.

Conclusion: The importance of a vicarious calibration cannot be overstated. Based on empirical studies conducted over the past 15 years with ocean color as well as atmospheric and land data, NIST has determined that vicarious calibration, using surface-truth measurements to compare with satellite measurements, is necessary to calibrate the sensor after the launch, including setting/re-setting the instrument gain factors.

Conclusion: MOBY or a MOBY-like effort is necessary for the continuation of ocean color climate data records. Although other approaches might produce acceptable vicarious calibration data, they have not been widely implemented or deployed operationally. MOBY is currently the accepted standard for a vicarious calibration source and is already deployed. Further, non-U.S. sensors (such

as MERIS) use MOBY as a vicarious calibration source, which will make it easier to link U.S. and international datasets.

Conclusion: To maintain SeaWiFS accuracies in retrieving water-leaving radiance, a sensor's overall uncertainty level for calibration gains needs to be constrained below 0.3 percent (see Appendix B). This can only be accomplished by a vicarious calibration, which needs to begin at the start of the mission to achieve this accuracy.

5. Stability Monitoring: Lunar Calibration or Another Proven Mechanism for Stability Monitoring Is Required to Achieve Radiometric Stability Goals

In addition to vicarious calibration, temporal changes in sensor radiometric calibration need to be determined throughout the mission, and corrections need to be made for observed rate of degradation, to ensure high-quality ocean color data (e.g., Eplee et al., 2004; McClain, 2009). The experience with SeaWiFS shows that different spectral channels degrade at different rates (Figure 3.4) and independent corrections must be applied to each spectral band.

Because of the success of the SeaWiFS lunar imaging-based stability monitoring, this methodology has been incorporated into the MODIS on-orbit performance analyses and adopted by other missions prior to launch, e.g., Ocean Colour Monitor on-board Oceansat-2 (OCM-2). It should be noted that this is a relative measurement, not an absolute calibration. MERIS employs an alternative approach using two solar diffusers: one with frequent solar observations to monitor the sensor stability, and a second diffuser with infrequent solar observations to monitor the degradation of the first. Multiple concurrent solar diffusers are important for assessing impacts of stability if the moon is not used as the standard. In addition to lunar views, solar diffusers may be required for stability monitoring of sensors such as MERIS that have multi-detector imagers, because lunar views image only a small portion of the observed area and include only a few detectors. The advantage of using the moon directly as a stability source is that the relatively weak and diffuse sunlight radiance reflected from the moon can be viewed directly through the same optics as the ocean, i.e., without using a diffuser or separate optical path to the satellite sensor. This minimizes concerns that diffuser characteristics can change during the satellite mission. In addition, observing the moon has the advantage of providing sensor observations acquired at radiance levels more nearly equivalent to top of the atmospheric Earth-viewed radiance.

For both SeaWiFS and MODIS-Aqua, individual spectral channels degraded at different rates with time (Figure 3.4). Over the first nine years of SeaWiFS observations, the 865-nm band degraded the most (18 percent). In contrast, for MODIS-Aqua, a sensitivity loss of 15 percent at 412 nm during a four-year period was the most for any of Aqua's ocean color bands (McClain et al., 2006). The relatively rapid and significant degradation of the SeaWiFS 865-nm band relative to the other spectral bands would have made accurate atmospheric correction difficult if not impossible to implement without applying the degradation corrections. It is equally important that the degradation be determined throughout the mission. An example is that while the SeaWiFS 865-nm band followed a well-characterized pattern during the first nine years of on-orbit operations, it subsequently changed its decay trend. Without ongoing measurements of sensor degradation, this important change in behavior would not have been detected, leading to deterioration of product accuracy.

Importantly, the deviations in the SeaWiFS lunar calibration observations from the fit equations used to correct for sensor drift are very small, here less than 0.1 percent. Note that the level of uncertainty in the stability characterization is less than the uncertainty in the vicarious calibration (see Appendix B) and points to the excellent qualities of the moon as a stability source for ocean color sensor characterization.

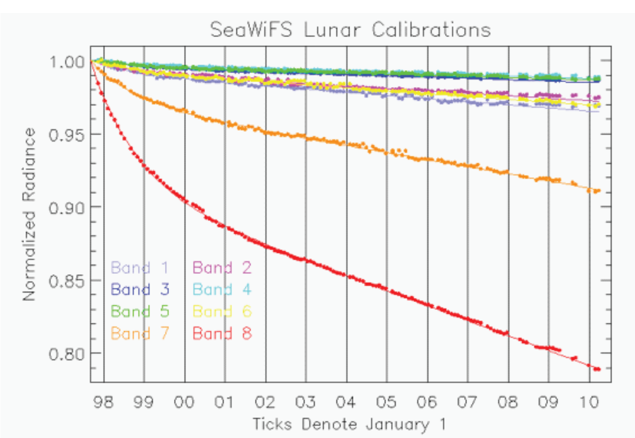


FIGURE 3.4 SeaWiFS lunar calibrations (Patt, personal communication, 2010). Deviations from the fitting functions are less than 0.1 percent for all bands.
SOURCE: Ocean Color Biology Group, NASA's Goddard Space Flight Center.

Conclusion: Stability monitoring is of highest priority. Monitoring instrument stability can constrain the sensor changes within 0.1 percent by viewing an appropriate source (such as the moon).

Recommendation: Future ocean color sensors should view the moon at least monthly through the Earth-view port to monitor the sensor's stability throughout its mission.

6. Mission Overlap Is Essential to Transfer Calibrations between Sensors (e.g., SeaWiFS was used to help transfer calibrations to MODIS)

Mission overlap was essential for enabling high-quality ocean color data from both the MODIS-Aqua and MODIS-Terra sensors. The calibration for MODIS, an instrument that shares a number of challenging design features with VIIRS, is complicated. It was fortunate that observations from SeaWiFS were available, with its well-studied calibration and product validation history and a sensor based on a simple design (e.g., constant angle of incidence scan system vs. MODIS variable angle incidence scan). Water-leaving radiances derived from SeaWiFS observations were employed as reference radiances to study the seasonal, latitudinal, cross-scan, and polarization behavior of the water-leaving radiances for MODIS on Aqua and Terra (Kwiatkowska et al., 2008; NASA, 2009b). These comparisons served to validate the various corrections used to determine the actual MODIS-Aqua polarization response. Eventually, MODIS-Aqua and SeaWiFS L_w converged. However, without access to well-characterized SeaWiFS products that had been validated against extensive in situ observations, accurate MODIS-Aqua L_w would not have been achieved. This underscores the justification for extensive pre-launch characterization.

Mission overlap also was required to assess the high quality of the MODIS-Terra dataset, which was complicated by time-dependent changes in the gains and polarization sensitivity as a function of scan angle (Kwiatkowska et al., 2008). Given these sources of uncertainty, the retrieval of climate-quality water-leaving radiance observations from the MODIS-Terra mission was possible only after comparison with near simultaneous data from SeaWiFS and MODIS-Aqua. To best account for these sources of uncertainty, a vicarious calibration procedure was employed for MODIS-Terra, using SeaWiFS as truth, to simultaneously correct for the time-dependent changes in gains and polarization sensitivity (Kwiatkowska et al., 2008; Franz et al., 2008). This demonstrates the utility of simultaneous satellite observations to best characterize on-orbit changes in instrument responses. This methodology of comparing multiple satellites also has been used in the on-orbit assessments of MODIS-Aqua responses (NASA, 2009b). We must also note the unfortunate fact that the VIIRS mission will not overlap with SeaWiFS.

Recommendation: New satellite missions need to demonstrate that their L_w measurements are consistent with those obtained by prior missions, particularly prior missions for which considerable validation and vicarious calibration data were obtained. This is an essential requirement for developing sustained ocean color time-series for scientific analyses.

7. End-to-End Validation of Ocean Color Products Is Critical and a Key Step in the Reprocessing of Ocean Color Data Products

Validation programs[4] are required to ensure that the algorithms that generate data products from satellite radiances are credible with data users and that the models and procedures used to process the datasets are working appropriately. Validation is also a key step in the reprocessing of ocean color data products (Figure 3.1). Algorithm development is an active area of research conducted by many independent research labs. To take advantage of community findings, an effort is required to compare and validate various algorithms and products. Validation programs for SeaWiFS and MODIS included comparisons of satellite with in situ L_w, i.e., comparisons of derived ocean color data products such as chlorophyll, particulate organic carbon (POC), particulate inorganic carbon (PIC), and CDOM with in situ data, and comparisons of aerosol characteristics used to correct for the atmospheric path radiance with field observations. Validation requires match-up datasets that can be used to compare satellite data performance with field observations (Bailey and Werdell, 2006). Given the high costs of ship time and other fixed costs, ideal validation programs produce comprehensive ocean-atmosphere datasets to meet multiple purposes. Appendix C describes the measurements needed for comprehensive datasets. Validation of aerosol data products is as essential as validation of in-water properties. For SeaWiFS and MODIS, aerosol validation was provided by measurements from a network of sun photometers (Knobelspiesse et al., 2004). The results of these comparisons are then used to assess how to improve the data products through iterative changes to sensor calibration and/or retrieval models (Figure 3.1).

To facilitate the algorithm development and data product validations for SeaWiFS, the Goddard Ocean Color Data Reprocessing Group maintains a repository of in situ marine bio-optical data, the SeaWiFS Bio-optical Archive and Storage System (SeaBASS; seabass.gsfc.nasa.gov). The acquisition and analysis of the in situ measurements has been an international collaboration (e.g., the Atlantic Meridional Transect program), which greatly enhances the global distribution of data in SeaBASS. Acquisition of these observations

[4] "Validation is the process of determining the spatial and temporal error fields of a given biological or geophysical data product and includes the development of comparison or match-up data set." From http://www.ioccg.org/reports/simbios/simbios.html.

is time consuming and resource intensive; sharing of data and resources across the community is vital to obtain adequate coverage in space and time. These data were used to compile a large set of pigment concentrations, biogeochemical variables, and inherent optical properties. This new dataset, the NASA bio-Optical Marine Algorithm Dataset (NOMAD), includes more than 3,400 stations of L_w, surface irradiances, and diffuse downwelling attenuation coefficients. Metadata, such as the date, time, and location of data collection, and ancillary data, including sea surface temperatures and water depths, accompany each record (Werdell and Bailey, 2005). Global data coverage is needed to create global bio-optical algorithms, to test their performance in particular regions, and to develop regionally specific algorithms.

Conclusion: To derive and validate the desired ocean color data products from water-leaving radiance, in situ data representing the range of global ocean conditions is needed for algorithm development and product validation. These in situ data need to be collected, properly archived and documented, and widely available through a database such as SeaBASS. The global requirements of this database suggest that these data are to be shared among all international participants.

Conclusion: All ocean color missions require product validation programs as a key step in the reprocessing of ocean color observations and to establish uncertainty levels for ocean color mission data products.

8. Satellite Ocean Color Products Need Continual Reprocessing to Assess Climate-Scale Changes in the Ocean Biosphere, and Reprocessing Is an Important Element in Developing Multi-Decadal Ocean Color Datasets

The importance of reprocessing mission data at regular intervals throughout the mission became apparent during both SeaWiFS and MODIS missions (McClain, 2009; Siegel and Franz, 2010). Much is learned during the mission about the sensor's behavior and the atmospheric correction, bio-optical, and data high-quality mask/flag algorithms for converting L_w into ocean color products. Data reprocessing is needed to adjust for the following changes: (1) to the calibration coefficients due to sensor degradation, (2) to in-water and atmospheric correction algorithms based on validation results, and (3) in availability of new algorithms for new and improved data products. In addition, as discussed above, it takes many match-ups before the vicarious calibration can achieve the desired accuracy and stability for the sensor's gain factor. Therefore, data processing and product generation cannot be expected to produce high-quality products at the beginning of a new mission.

For all these reasons, data product quality will improve as more is learned about the sensor's behavior and as a result of reprocessing. For example, the initial processing of SeaWiFS imagery yielded negative values for water-leaving radiance for continental shelf waters in the band centered at 412 nm and depressed values at 443 nm. This difficult problem was not fully resolved until the data were reprocessed many times (e.g., Patt et al., 2003; McClain, 2009). In 2009, the reprocessing of the MODIS-Aqua dataset corrected another, much more subtle drift in the 412-nm water-leaving radiance, which had resulted in an apparent dramatic increase in CDOM concentration in the open ocean (Maritorena et al., 2010).

Reprocessing requires appropriate computational tools so that the entire dataset can be processed rapidly, enabling changes between algorithm or calibration selections to be quickly evaluated. This ability to rapidly reprocess the entire data stream was planned for the SeaWiFS mission. Fortunately, the price to performance ratio for commodity computer hardware has decreased dramatically since the launch of SeaWiFS, which makes it much easier to configure and run reprocessing experiments with multiple datasets.

Reprocessing of ocean color datasets also is critical for developing decadal-scale records across multiple missions. Antoine et al. (2005) developed a decadal-scale ocean color data record by linking the CZCS data record to the SeaWiFS era. Key to their approach was the reprocessing of both datasets using similar algorithms and sources. The resulting decadal ocean color time-series shows many interesting climate patterns supporting their approach (Martinez et al., 2009). Thus it is likely that the best approach to creating multi-decadal ocean color data products is the simultaneous reprocessing of multiple ocean color missions with similar algorithms and the same vicarious calibration sources, if possible (Siegel and Franz, 2010).

Conclusion: Reprocessing is important and needs to be incorporated into the mission plan and budget process from the beginning, with provisions for the computational ability to rapidly reprocess the entire dataset as it increases in size.

Conclusion: Reprocessing of multiple missions referenced to the same vicarious calibration sources is likely the only way to construct long-term ocean color data products.

9. The External U.S. and International Science Community Needs to Be Routinely Included in Evaluating Sensor Performance, Product Validation, and Other Updates to Ocean Color Data Products

One of the unique strengths of the SeaWiFS mission was how well it engaged the U.S. and international science community of ocean color data users, as well as those with technical knowledge and insight on satellite data processing and bio-optical measurements. Although all NASA science missions have science teams, the Ocean Biology and Biogeochemistry program is unique in hosting annual Ocean

Color Research Team meetings that are open to anyone. In this way, the SeaWiFS Project received input from a broad international group of scientists on algorithms, data quality, data products, validation, and other topics, from pre-launch throughout the mission. As a result, the project received important and unanticipated contributions that led to significant improvements. For example, the at-launch chlorophyll algorithm for SeaWiFS (OC-4) emerged from a community-led meeting that compared a wide suite of model formulations (O'Reilly et al., 1998). Another important advantage of open engagement is that the international user community develops a sense of ownership of the mission, which leads to considerable international cooperation. For example, members of the SeaWiFS project involved with algorithms and validation were invited as participants in the United Kingdom-supported Atlantic Meridional Transect cruises (Aiken et al., 2000), which provided a key source of in situ data across many bio-optical regimes.

Conclusion: Annual ocean color technical meetings among U.S. and international researchers and space agency personnel will create many opportunities for cooperative calibration and validation programs, improvements to algorithms, and coordination of ocean color mission data reprocessing.

10. Open and Efficient Access to Ocean Color Raw Data, Derived Data Products, and Documentation of All Aspects of the Mission is Required

The strong engagement of the research community would not have been possible without SeaWiFS's exemplary open data policy and the ease with which data could be accessed. The implementation of an open access data policy with an efficient data distribution system built support for the mission. Such open data policies are the cornerstone for ensuring the robustness of the scientific method. In contrast, an open data policy with an inefficient data system can be problematic. An ocean color data system has to include a browse capability, as well as a way to distribute large amounts of data over the Internet (see Acker et al., 2002b). The ease of use of the SeaWiFS data system has made it the standard among ocean color missions. This was driven largely by researchers and engineers at the NASA SeaWiFS project. During the SeaWiFS and MODIS missions, many users wanted Level 3 imagery (i.e., maps of a particular product such as chlorophyll), whereas sophisticated users wanted Level 1 or Level 2 data to implement special algorithms and processing and to generate full-resolution, mapped imagery for a specific ocean region. Users generating long time-series of science or climate-quality imagery across multiple satellite data streams want access to Level 0 data, or if not Level 0 data, then a data level and ancillary information that allows "tweaking" of the calibration coefficients.

However, U.S. ITAR restrictions may hinder international exchange of raw satellite data and detailed calibration information. Such restrictions could seriously impede international cooperation, making it even more challenging to produce long time-series of ocean color products that are essential for determining if the ocean biology is changing in response to a changing climate.

ITAR restrictions may present the biggest problems when users attempt to exchange information about the sensor characteristics. Algorithms and reprocessing details are generally well documented for NASA ocean color satellite missions, including SeaWiFS and MODIS. The SeaWiFS project also documented many important technical and other aspects of the mission, producing 43 pre-launch and 29 post-launch technical reports on topics such as optics protocols, description of the bio-optical archive, results of inter-calibration exercises for in situ measurements, and orbit analysis. These documents are extremely valuable to users and to those planning future missions, including international partners. For the recent satellite ocean color reprocessing effort, these printed documents appear first as Web-based reports[5] that show the effects of virtually every change on the final data products.

Conclusion: Efficient data systems, which are responsive to users' needs and provide well-documented information on data algorithms and reprocessing, make important contributions to successful ocean color missions.

CONCLUSION

Based on lessons from CZCS, SeaWiFS, and MODIS, the committee concludes that requirements to successfully sustain ocean color radiance measurements from space go far beyond the specifications of a single sensor or mission. Delivering high-quality ocean color products demands long-range planning and long-term programs with stable funding that exceed the lifetime of any particular satellite mission.

Most of the important lessons from CZCS, SeaWiFS, MODIS, and MERIS relate to aspects of those missions that are not directly linked to the sensors' design or specifications. However, much of the effort and budget to prepare the JPSS/NPP mission has been dedicated to sensor design, with relatively scant attention to long-range planning and other elements described in this chapter. Therefore, it is worth reiterating that launching a robust sensor into space meets only one of many requirements to successfully obtain ocean color radiance from space.

The SeaWiFS mission incorporated important lessons learned from the CZCS, such as the need for sensor stability monitoring, vicarious calibration, an in situ calibration/validation program, and a dedicated team for data processing, reprocessing, and distribution. As a result, SeaWiFS became

[5] See http://oceancolor.gsfc.nasa.gov/WIKI/OCReproc.html.

a successful mission and is considered the "gold standard" for a Type 1 mission.

Although some coastal applications are not well served by SeaWiFS, the SeaWiFS sensor and the manner in which the mission was operated set an excellent standard by which to judge minimum sensor and mission operations requirements to generate data products for researchers, to assess climate impacts, and to deliver products for many operational users.

Minimum requirements for sensor design have to be assessed in the context of the specific application. A single set of requirements will not be able to deliver the broad spectrum of ocean color products necessary to meet the needs of the user community.

Because the sensor designs vary considerably, it is impractical for the committee to prescribe a particular design feature for future missions. Nevertheless, the design choices need to meet some key requirements, as listed in Table 3.2. It is important to weigh the trade-offs of each design element, because some choices will make other aspects of the mission more difficult.

Recommendation: To contribute to the success of a Type 1 mission, the sensor should meet some key design requirements. In particular, the sensor should:

- ***Minimize the impacts of scan geometry on the processing of ocean color imagery.***
- ***Minimize sun glint by tilting the scan away from the sun-glint patterns.***
- ***Measure atmospheric signal in both ocean color and aerosol bands without saturation yet provide sufficient precision in the ocean color bands.***
- ***Have minimal but well-characterized polarization sensitivity.***
- ***Have at least the SeaWiFS band-sets plus MODIS chlorophyll a fluorescence bands.***
- ***Be well characterized and tested pre-launch.***

In addition to the sensor requirements above, the committee suggests that minimum standards of design (Table 3.3) and characterization and calibration (Table 3.4) be followed for new satellite ocean color sensing systems, so that the best possible data are produced within the constraints of individual programs.

All new sensors are required to have high radiometric accuracy and stability. The committee recognizes that the costs associated with these standards, as represented by such instruments as MODIS and VIIRS, are very high. Although SeaWiFS standards could be relaxed for some operational users who only require pattern recognition, that would serve a comparatively small group among the total current research and operational users of satellite ocean color data (see Chapter 2). It also seems illogical to build and launch a satellite system that would achieve only these goals when a wider range of objectives could be fulfilled with some

TABLE 3.2 Sensor Requirements for Global 1 Km Ocean Color Remote Sensing to Sustain Both SeaWiFS and MODIS Measurements

Geophysical Measure	Data Character	Sensor Parameter	Minimum Requirements
Ocean Color Radiance	Spectral Coverage	Band-set	360, 385, 412, 443, 490, 510, 555, 667, 678[a] nm
	Sensitivity	Signal-to-Noise Ratio (SNR)	SeaWiFS SNR in high gain mode
	Spectral Purity	Out-of-band rejection Cross-talk	Better than for SeaWiFS
	Radiometric Purity	Polarization sensitivity Stray light rejection	< 1 percent
		Response vs. scan angle (RVS)	Better than for SeaWiFS
	Geometric Stability		
Aerosols	NIR Coverage	NIR band-set	765 and 865 nm with appropriate SWIR bands
	Sensitivity	SNR	Similar to MODIS for the NIR bands but >MODIS for the SWIR
Clouds and Land	Dynamic Range	No saturation	Auto gain control
Global Daily Ocean Coverage	Sun Glint Avoidance	Off-nadir pointing	Tilting from sun-glint pattern
Stability	Calibrated	On-orbit reference	Solar diffuser and monthly lunar view Lab calibration
		Pre-launch characterization	~0.1 percent stability compared with trend line

NOTE: ('>' signifies "better than").

[a] The 678-nm band is needed for chlorophyll fluorescence line height determination as done in MODIS and should be at an enhanced sensitivity compared with the other visible bands.

TABLE 3.3 Ocean Color Performance Design Guidelines That Affect Sensor Performance for Ocean Color and Other Applications

Sensor Element	Performance Design Guideline	Sensor Example
Pointing/Scanning	Stray light rejection, high transmittance, low response vs. scan (RVS) angle variation	SeaWiFS forebaffle limits far-field stray light, half-angle mirror reduces RVS
Optics	High transmittance, flat field response, achromaticity	MODIS afocal telescope flat field high transmittance
Spectral Separation	Flat bands, sharp cutoffs, low out-of-band response, high transmittance	MODIS, SeaWiFS, VIIRS discrete interference filters
Detectors	Low noise, flat response over band, low inter-detector cross-talk, low detector-to-detector variation	SeaWiFS "single-detector" per band avoids non-uniformity
Electronics	Low noise, high frequency response, minimum channel-to-channel variation	SeaWiFS "single-channel" per band avoids channel-to-channel variation

Examples of sensors from Tables 3.2 and 3.3 are indicated in the far right columns to illustrate applications of the principles.

TABLE 3.4 Ocean Color Pre-launch Characterization and Calibration (C&C) Design Guidelines That Affect Characterization, Calibration, and Sensor Stability Costs and Inherent Accuracies

Sensor Element	C&C Design Guideline	Sensor Example
Pointing/Scanning	Response vs. scan (RVS) angle variation and polarization sensitivity	MODIS RVS cost driver with two-sided paddle-mirror
Optics	Spectral polarization sensitivity, transmittance, & modulation transfer function (MTF) vs. field angle	
Spectral Separation	Spectral acuity, flatness, out-of-band response, spatial uniformity	
Detectors	Cross-talk, linearity, MTF, SNR, detector-to-detector uniformity	SeaWiFS single-detector design limits non-uniformity
Electronics	Channel-to-channel variation, frequency response, linearity, noise	

Examples of sensors from Tables 3.2 and 3.3 are indicated in the far right columns to illustrate applications of the principles.

additional investment and effort. Sustaining SeaWiFS sensor and mission operation standards are the minimum criteria for satisfying the current research and operational applications for ocean waters beyond the shallow (< 20 m depth) waters near the coast. However, it needs to be stressed that many current research questions require that the sensor and mission meet more than just the minimum requirements. As discussed in Chapter 5, meeting only the minimum requirements will not be sufficient to explore the full potential of ocean color to generate novel products. Of course, without access to the novel products, one would not be in a position to undertake any research and development activity that required access to such products. The minimum requirements as stated are what are required to maintain the status quo in ocean color research and applications, and to sustain and further develop applications that require long, consistent time-series data. Meeting the minimum requirements would ensure that we do not lose ground so painstakingly gained, but would not ensure that we maintain preeminence in the field.

One area in which the committee concluded that requirements could be relaxed is pre-launch calibration accuracy requirements. Because a Type 1 ocean color sensor will undergo a vicarious calibration, meeting pre-launch standards becomes less crucial to the success of the mission as long as the other aspects of pre-launch characterization (spectral tests, polarization tests, etc.) and a successful on-orbit sensor stability-monitoring program are conducted. A pre-launch absolute calibration of only 3 to 5 percent (rather than approaching the 0.3 percent on orbit vicarious calibration requirement) would reduce costs for the launch characterization.

Recommendation: Based on the lessons described in this chapter, the committee has identified 13 essential requirements to successfully obtain ocean color data from a Type 1 remote sensing mission. Mission planning and funding should include and support the following requirements:

1. ***The sensor needs to be well characterized and calibrated prior to launch and needs to be equivalent to the combined best attributes from SeaWiFS and MODIS;***
2. ***Post-launch vicarious calibration using a MOBY-***

like approach is required to set the gain, to assess the through-system calibration, and to constrain the accuracy of the ocean color data products;

3. Stability monitoring is needed to assess and correct for ocean color sensor degradation (e.g., approximately monthly lunar look);

4. At least six months of sensor overlap is needed to transfer calibrations between sensors and to produce continuous climate data records;

5. Atmospheric correction and bio-optical models need to be updated as advances in science and observations become available;

6. Ocean color data products need to be validated over the range of global ocean conditions and feedback of data product validation to model improvement and on-orbit sensor characterization needs to occur. This validation plan needs to support in situ sampling of appropriate data for ocean color data product validation including the atmospheric correction bands and products;

7. Support research on algorithm and product development;

8. Ocean color data products need to be reprocessed periodically to incorporate changes to calibration owing to sensor degradation and algorithm improvements. Level 0 data need to be permanently archived to allow reprocessing;

9. The construction of long-term ocean color data records requires that satellite data from multiple missions be reprocessed using the same vicarious calibration sources and similar algorithms;

10. The U.S. and international science community should be routinely included in evaluating sensor performance, product validation, and supporting research on ocean color applications;

11. A system is needed that makes freely available all raw, meta-, and processed ocean color data products, algorithms, and processing codes that can distribute the data rapidly and efficiently;

12. Detailed and comprehensive documentation of all aspects of the mission needs to be accessible (instrument, algorithms, in situ protocols, etc.); and

13. Institutional memory needs to be maintained to ensure transfer of knowledge and expertise from previous mission science and engineering teams to subsequent U.S. groups and international partners.

It is important to reemphasize that these requirements represent the minimum necessary to continue ocean color remote sensing and to maintain current research and operational uses. To advance the science, missions need to go beyond the current capabilities. These next steps are discussed in Chapter 5. In addition, as we learned from past experience, every mission presents the community with new and unanticipated challenges that require hardware or software fixes or other approaches to circumvent the mission's shortcomings.

Every satellite ocean color sensor launched so far has been unique, different from its predecessors and successors. Each mission's objectives, of necessity, focused on optimizing the performance of the algorithms tailored specifically for that sensor. What all satellite sensors have in common, however, is a finite lifetime (SeaWiFS, with the longest service so far, provided valuable data for 13 years). And yet, when the goal of a study is to examine long-term trends and to isolate natural variability from climate change, the need is for climate-quality data records that extend over several decades: The longer the data record, the higher the value of the data stream, in the climate-change context. It is impossible to meet such goals with data from a single satellite; merged data from multiple satellites are critical to create the longest possible times-series of high-quality data. The goal then becomes continuity of data and products, rather than the success of any single mission. We know now that we cannot reach the goal of studying the marine ecosystems in the context of a changing climate except through international collaboration and merging of data from multiple satellites. As discussed in greater detail in Chapter 5, meeting the diverse needs of the expanding ocean color user community will require multiple sensors in both polar and geostationary orbit (Appendix D). An internationally shared effort to meet that requirement would yield benefits for all. Thus, an ideal planning approach moves beyond the mission-centric toward a data-centric approach

4

Capabilities of Current and Planned Ocean Color Sensor Missions

The previous chapter discussed the essential requirements for a successful ocean color mission (including requirements for sensor design, stability monitoring, vicarious calibration, and a calibration/validation program). This chapter examines the capabilities of planned sensors and missions to meet these requirements. We provide only a brief description of current and planned ocean color satellite sensors (for details see Appendix A). The chapter compares the sensors' capabilities to the minimum requirements outlined by the committee, with commentary on design approaches that enhance data accuracy and stability. In addition, it assesses the likelihood that these sensors will deliver products of sufficient quality. As discussed in Chapter 2, a single sensor or mission cannot meet the needs of all ocean color products. Because the charge to the committee is limited to Type 1 and 2 sensors, this analysis focuses on their capabilities.

CURRENT AND PLANNED OCEAN COLOR SENSORS

Figure 4.1 illustrates the timeline for past and planned launches of U.S. and foreign ocean color sensors. Launches of the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) and Moderate Resolution Imaging Spectroradiometer (MODIS) sensors were closely spaced, which resulted in a continuous U.S. data stream for remotely sensed ocean color. This close spacing resulted in sensor overlap, which made it possible to intercalibrate these sensors (for details see Chapter 3). However, SeaWiFS just recently ceased operations and the only other U.S. sensor in orbit, MODIS, is beyond its planned life span. The next U.S. sensor, Visible Infrared Imager Radiometer Suite (VIIRS) on National Polar-orbiting Operational Environmental Satellite System (NPOESS) Preparatory Project (NPP), is not planned for launch until fall 2011 or later. Therefore, U.S. scientists are at risk of losing access to an ocean color data stream. The Medium-Resolution Imaging Spectrometer (MERIS) is currently operating, although it is also beyond its design lifetime. While a foreign Type 2 sensor has recently been launched (Ocean Colour Monitor on-board Oceansat-2 [OCM-2]), questions of data access and data quality assurance need to be resolved, as discussed below.

Details of the character of each currently operating sensor are listed in Table 4.1. Characteristics of planned launches are listed in Table 4.2 (additional details in Appendix A).

As discussed in Chapter 2, the diverse set of data specifications required to meet all ocean color user needs requires different types of satellite sensors. Figure 4.1 shows that many sensors will be available, but Tables 4.1, 4.2, and 4.3 illustrate that they vary widely, each with its own capabilities and limitations. Although nine ocean color satellite missions have been launched to date, only four (CZCS, SeaWiFS, MERIS, and MODIS-Aqua) have acquired high-quality global observations. This record raises concerns for the probability of success of the upcoming missions shown in Figure 4.1.

For example, data from the MODIS-VIIRS line of sensors can provide routine coverage of the global ocean at 1-km resolution. But U.S. users need access to other polar-orbiting satellite ocean color data streams for (1) coastal and other applications, (2) to improve coverage of the global ocean using merged datasets from multiple sensors, and (3) as a backup for global coverage in the event of a failure of a U.S. sensor. The sensors with known or likely capabilities to serve these needs are MERIS on the European Space Agency's (ESA) Environmental Satellite (ENVISAT), Ocean Land Colour Instrument (OLCI) to be flown on ESA's Sentinel 3A and 3B satellites, Second-Generation Global Imager (S-GLI) to be flown by Japan Aerospace Exploration Agency (JAXA), and OCM-2, currently operating in space and maintained by the Indian Space Research Organization (ISRO). Data from other polar orbiting sensors may also be available, but their characteristics and mission operating procedures are less well known to the U.S. community.

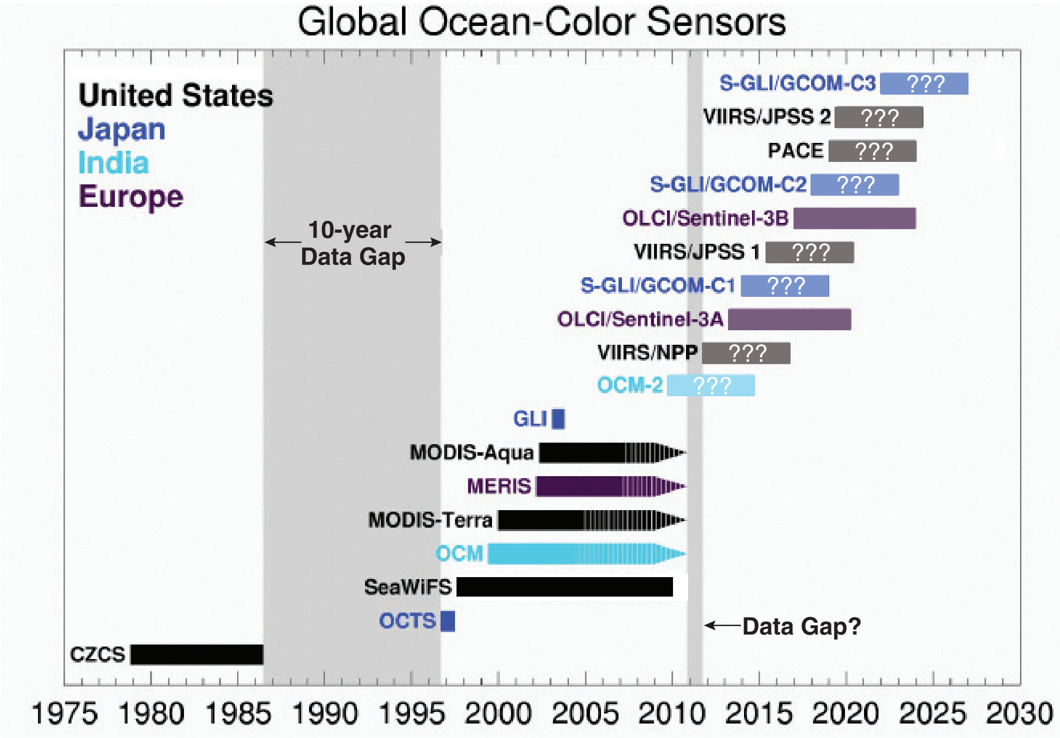


FIGURE 4.1 The launch sequence of past, current, and planned ocean color sensors in polar orbit are displayed. The sensors still operational are shown with a one-sided arrow; the hatched area indicates when a sensor is beyond its design life. The gray shaded background indicates a data gap in the past and a potential data gap arising if MODIS sensors and MERIS cease today. The question marks are used to indicate sensors that either do not yet meet the minimum requirements or are vulnerable to changes in funding allocation. Future sensors are shown having either a five- or seven-year lifetime, according to their individual specifications. CZCS: Coastal Zone Color Scanner; OCTS: Ocean Color and Temperature Scanner; SeaWiFS: Sea-viewing Wide Field-of-view Sensor; OCM/OCM-2: Ocean Colour Monitor; MODIS-Terra/MODIS-Aqua: Moderate Resolution Imaging Spectroradiometer on Terra/Aqua, respectively; MERIS: Medium Resolution Imaging Spectrometer; GLI: Global Imager; VIIRS: Visible Infrared Imager Radiometer Suite; OLCI: Ocean Land Colour Instrument onboard Sentinel-3; PACE: Pre-Aerosol-Clouds-Ecosystem; GCOM-C: Global Change Observation Mission for Climate Research; JPSS: Joint Polar Satellite System. SOURCE: Based on data from http://www.ioccg.org/sensors_ioccg.html.

TABLE 4.1 Current Sensors in Space Having Spectral Bands and Other Specifications That Provide Type[a] 1 or 2 Ocean Color Sensor Capabilities

Sensor/Satellite/Type	Agency	Launch Date	Swath (km)	Spatial Resolution[b] (m)	Bands (visible/total)	Spectral Coverage (nm)
MODIS/Terra/1	NASA (USA)	1999	2,330	250/500/1,000	9/36	405-14,385
OCM-1/IRS-P4/2	ISRO (India)	1999	1,420	360/4,000	7/8	412-885
MERIS/2	ESA (Europe)	2002	1,150	300/1,200	12/15	412-1,050
MODIS/Aqua/1	NASA (USA)	2002	2,330	250/500/1,000	9/36	405-14,385
OCM-2/Oceansat2/2	ISRO (India)	2009	1,420	360/4,000	7/9	400-900

Listed in ascending order of launch date (for details see Appendix A).

[a] Sensors are characterized into Type 1-4 based on their spatial and spectral coverage and orbit (see Table 2.1).

[b] The sensor has some capability to sample at higher spatial resolution.

Conclusion: U.S. research and operational users of satellite ocean color data will have to rely on multiple sources, including sensors operated by non-U.S. space agencies, because the United States does not have approved missions that will sustain optimal ocean color data for all applications.

ANALYSIS OF CAPABILITIES AND GAPS

Our analysis of current and future capabilities is focused on the Type 1 and 2 sensors listed in Table 4.2 (those capable of providing global coverage approximately every two to three days), because most of the past experience is limited to

TABLE 4.2 Planned Sensors Having Spectral Bands and Other Specifications That Provide Type 1 and 2 Ocean Color Capabilities

Sensor/Satellite/Type	Agency	Launch Date	Swath (km)	Spatial Resolution (m)	Bands	Spectral Coverage (nm)
VIIRS/NPP/1	NOAA/NASA (USA)	2011	3,000	370/740	22	412-11,800
OLCI/Sentinel-3A/2	ESA/EUMETSAT (Europe)	2013	1,270	300/1,200	21	400-1,020
S-GLI/GCOM-C	JAXA (Japan)	2014	1,150-1,400	250/1,000	19	375-12,500
VIIRS/JPSS/1	NOAA/NASA (USA)	2016	3,000	370/740		412-11,800
OLCI/Sentinel-3B/2	ESA/EUMETSAT (Europe)	2017	1,265	260	21	390-1,040
PACE/2	NASA (USA)	2019				
VIIRS/JPSS1/1	NOAA (USA)	2019	3,000	370/740	22	412-11,800
ACE/2	NASA (USA)	202X		1,000	Hyperspectral at 5 nm; 3 discrete SWIR bands	350-2,130

Listed in ascending order of scheduled launch date.

TABLE 4.3 Planned Type 3 Sensor(s)

Sensor/Satellite	Agency	Launch Date	Swath	Resolution	Bands	Spectral Coverage (nm)
HyspIRI	NASA (USA)	Unknown	600 km	60 m	Hyperspectral at 10 nm	380-2,500

sensors of that type and because our goal is to assess options to ensure continuity in global ocean color data. The other sensors are critical to advance research applications, but as new sensors they are not essential to the continuity of the long-term global ocean color time-series.

Based on freely available information, the committee assessed whether current and planned sensors would meet some of the elements essential to the success of an ocean color mission, as listed in Chapter 3 (Table 4.4): pre-launch instrument characterization and calibration, post-launch stability monitoring, sun-glint avoidance, vicarious calibration, data processing and reprocessing, freely available user-friendly processing software, and availability of raw data and information on instrument characterization. These last two data-related requirements are of particular importance to climate and other scientific applications.

Table 4.5 lists the spectral bands for the sensors identified in Table 4.4, showing wide agreement among agencies and nations regarding the most important spectral capabilities for ocean color that are required to sustain current capabilities. A notable exception is the VIIRS sensor on NPP and Joint Polar Satellite System (JPSS), which is missing the 510- or 530-nm bands. Given the advances in ocean color algorithms for turbid waters (Morel and Bélanger, 2006), the result of these missing wavebands will lead to sub-optimal retrievals of chlorophyll and possibly other derived products in turbid coastal waters. Moreover, the large spectral gap between 555 and 665 nm has been problematic for remote sensing of coastal and shallow water habitats. For example, a band at 640 nm is critical for semi-analytical inversion models in coastal waters (Lee algorithm in IOCCG Report 5, 2006). Also, many sensors are missing the fluorescence bands.

The signal-to-noise ratio (SNR) of all wavebands on MERIS and VIIRS (both on NPP and JPSS) are equivalent to or better than the SNR for the wavebands on the SeaWiFS sensor (NOAA, 2010). In particular, reduction of the digitization of the NIR channels in SeaWiFS was an important source of noise in open ocean retrievals (Hu et al., 2004). The SNRs for 412-, 443-, 490-, and the 510-nm bands on OCM-2 and in the 761-nm band on OLCI and Second-Generation Global Imager (S-GLI) are worse than for respective bands on SeaWiFS (NOAA, 2010). All sensors listed in Tables 4.2 and 4.3 have been or are being designed to offer measures of the satellite radiances in various visible, NIR and/or short-wave infrared (SWIR) spectral bands, as well as for land applications. These latter bands are and will continue to be important for atmospheric corrections.

ENSURING GLOBAL HIGH-QUALITY OCEAN COLOR DATA FOR THE NEXT TWO TO FIVE YEARS

The greatest risk identified by the committee is that U.S. scientists and resource managers will lack access to high-quality ocean color data between now and the launch of Pre-Aerosol-Clouds-Ecosystem (PACE) (planned for 2019).

TABLE 4.4 Comparing SeaWiFS with Current and Planned Sensors Against Some Important Sensor and Mission Requirements

	SeaWiFS	MODIS-Aqua	MODIS-Terra	VIIRS NPP	VIIRS JPSS-I	PACE	ACE	MERIS	OLCI	OCM	OCM-2	S-GLI
Pre-launch Instrument Characterization	Yes	Yes	Yes	Yes	TBD	Mission requirement	Mission requirement	Yes	Yes	TBD	TBD	TBD
Stability Monitoring (lunar calibration or solar diffuser)	Yes; monthly lunar look	Yes; single solar diffuser with stability monitor; monthly views of the moon	Yes; single solar diffuser with stability monitor; monthly views of the moon	No; single solar diffuser with stability monitor, occasional views of the moon	TBD; single solar diffuser with stability monitor, occasional views of the moon	Mission requirement	Mission requirement	Yes; dual solar diffuser	Yes; dual solar diffuser	No	Planned two times per year	Yes; solar diffuser and monthly lunar look
Sun-Glint Avoidance	Yes; tilts	Mid-AM/ mid-PM orbits compensate	Mid-AM/ mid-PM orbits compensate	No	No	Mission requirement	Mission requirement	No	Yes, permanent across track tilt	Yes; tilts	Yes; but optimized for the Indian Ocean	Yes
Vicarious Calibration	MOBY	MOBY and SeaWiFS	MOBY and SeaWiFS	TBD; assumed use of MOBY	TBD; assumed use of MOBY	Mission requirement	Mission requirement	Planned for 2011 to use MOBY, Boussole	Planned to use MOBY, Boussole	No	Asked for MOBY	Assumed use of MOBY
Data Reprocessing	Yes	Yes	Yes	No	TBD	Mission requirement	Mission requirement	Yes	Yes	Unknown	TBD	Planned
Participates in a Continuity Plan for Heritage Missions	Yes	Yes (via SeaWiFS)	Yes (via SeaWiFS)	No	TBD	Mission requirement	Mission requirement	Yes	Yes	No	Member of OCR-VC	Yes
Data Exchange agreement for L-0 and L-1 data	Yes	Yes	Yes	No	TBD	Likely	Likely	TBD	TBD	TBD	TBD	Yes

Sensors from U.S. agencies are listed in white fields, from the European Space Agency in purple, from India in teal-colored fields, and from the Japanese space agency in blue.
SOURCE: Adapted from National Oceanic and Atmospheric Administration's Report, *Ocean Color Satellite Continuity Mitigation Plan Revision 2, Final Report*.

TABLE 4.5 SeaWiFS Spectral Bands and Those of Current and Planned Sensors

	Ocean Color Data Sources								
Band Center	SeaWiFS Band	MODIS-Aqua Band	MODIS-Terra Band	MERIS Envisat Band	OCM-2 Oceansat Band	OLCI Sentinel 3A & 3B Band	S-GLI GCOM Band	VIIRS NPP Band*	VIIRS NPOESS/JPSS Band*
412	412	412	412	412.5	412	413	412	412	412
443	443	443	443	442.5	443	443	443	445	445
490	490	488	488	490	490	490	490	488	488
510	510	531	531	510	510	510	530		
555	555	551	551	560	555	560	565	555	555
670	670	667	667	665	620	665	674	672	672
678		678	678	681					
765	765	748	748	778.8	740	778	763	746	746
865	865	869	869	865	865	865	869	865	865

Note band differences among the sensors.
SOURCE: Adapted from National Oceanic and Atmospheric Administration's Report, *Ocean Color Satellite Continuity Mitigation Plan Revision 2, Final Report*.

This high risk results from a combination of factors: the loss of SeaWiFS, the quality and age of the MODIS sensors, concerns with aspects of the VIIRS/NPP mission, and lack of adequate data access to foreign sensors. Concerns with the VIIRS/NPP mission result from uncertainty regarding the quality of and access to data. To minimize the risk of a data gap, this section will assess the three sensors most likely in orbit and capable of delivering ocean color data in the near term, with regard to their ability to meet key requirements.

MERIS Assessment

As discussed in the previous chapter and indicated in Table 4.5, the MERIS sensor was well characterized and calibrated pre-launch (Rast et al., 1999). In fact, the committee concludes that this careful characterization contributed significantly to the mission's success.

Although the MERIS mission is not designed to use lunar looks for stability monitoring, its approach of using dual solar diffusers appears to be adequate to monitor the sensor's stability. MERIS uses one solar diffuser every two weeks; the second is used every three months to check the stability of the first. The second diffuser is assumed to offer constant reflectance, which provides a check on the reflectance change of the first. The last calibration analysis shows a 1.5 percent degradation of the diffuser between 2002 and 2010 in the blue (443 nm) band and no detectable degradation in other bands.

Because of the careful pre-launch characterization and calibration, a vicarious calibration was initially assumed to be unnecessary. However, the benefit of the vicarious calibration has been subsequently recognized (Antoine et al., 2008). Marine Optical Buoy (MOBY) and BOUSSOLE (Bouée pour l'acquisition de Séries Optiques à Long Terme; Antoine et al., 2006, 2008) were used for this purpose and the calibration has been completed. BOUSSOLE is a joint European ocean color calibration and validation activity to which NASA also contributes.

The MERIS sensor is not tilted to avoid sun glint. Pixels with "moderate sun glint" are identified and a correction is applied to increase the coverage area (Bézy et al., 2000). Pixels with higher levels of sun glint are simply flagged and users are left to judge whether they can use the data or not.

Level 0 data generally are not available to users. This is only of concern to those users who may want to process and reprocess the data with the original raw data (see previous discussion in this report). Level 1 data are available in near-real time (about three hours after acquisition) and again after processing for accuracy, within about three weeks (Bézy et al., 2000). Level 2 data also are freely available and mapped. MERIS data have been used in particular in producing the multi-sensor global *GlobColour* merged data products (Maritorena et al., 2010). A major reprocessing of the entire mission has been achieved, which includes a Level 2 vicarious calibration similar to the one applied to the NASA SeaWiFS and MODIS instruments (e.g., Gordon, 1998; Franz et al., 2007) that improves compatibility across these missions.

The ocean color group at the National Aeronautics and Space Administration's (NASA's) Goddard Space Flight Center (GSFC) typically prefers to work with Level 0 data but can use as an alternative Level 1B imagery. Such imagery is available so long as ESA provides updates and the GSFC group has access/insight to the sensor issues, as is currently the case through GSFC participation in the MERIS "Data Quality Working Group" (DQWG). Although Level 3 data have become available recently, some U.S. users were discouraged that they did not have access to Level 3 data from the mission's start.

Conclusion: The MERIS mission and sensor design meet most requirements and show great promise for data to reach climate quality. Incorporating NASA scientists into ESA's MERIS Data Quality Working Group is a very positive development that ideally would continue.

OCM-2 Assessment

All sensors currently in polar orbit are beyond their design lives, with the exception of OCM-2. If these sensors fail, OCM-2 will be the only ocean color sensor in space until the launch of VIIRS on NPP. Therefore, this sensor might become an important component of a mitigation plan to minimize a data gap.

The committee was not able to review the status of the pre-launch characterization and calibration due to lack of information. Importantly, OCM-2 assesses sensor stability using solar and lunar calibrations. ISRO has established a cal/val optical buoy in the Lakshadweep Sea to perform a vicarious calibration.

OCM-2 tilts the sensor twice per year to avoid the sun glint over the Indian Ocean. Thus, the current sun-glint avoidance mechanism is optimized for the Indian Ocean. Because of this constraint, the mission is not designed to acquire global data.

Although India is a member of the virtual ocean color constellation group and has plans to make products available online, no data agreements have yet been established to access data from OCM-2 for U.S. investigators. However, the U.S. and Indian space agencies have held productive discussions to negotiate data exchange agreements.

Because OCM-2 is the only ocean color sensor in orbit that has not exceeded its design life, negotiating data access from the Indian Space Agency is the only option to avoid losing near-term access to ocean color data, if the older sensors fail. Even if U.S. users acquire access to the data, at present it is difficult to assess whether this sensor could produce climate-quality ocean color products. For example, the tilt of OCM-2 is currently optimized only for the Indian Ocean; however, OCM-2 views the moon and the sun to assess sensor stability. Before it can be determined whether OCM-2 products will be of equivalent high-quality to SeaWiFS products, access to data, including characterization and calibration data, needs to be worked out. In addition, it is unclear at this point if the mission's operations can include global coverage. For OCM-2 to meet the requirements of a vicarious calibration, routine reprocessing and stability monitoring need to be implemented. Therefore, it is not yet possible to determine whether OCM-2 can provide climate-quality global data. Finally, there is no plan to routinely access OCM-2 data, although NOAA has successfully negotiated access to vector wind data from Oceansat-2.

Conclusion: Many issues are unresolved with regard to the high quality of and access to OCM-2 data.

Conclusion: Because of the age of MERIS and MODIS, data availability from these sensors may be lost soon. Therefore, OCM-2 and VIIRS on NPP may be the only Type 1 and 2 ocean color missions in orbit until the launch of JAXA's S-GLI and ESA's OLCI sensors. Therefore, data access to OCM-2 may be the only option to mitigate a data gap, if VIIRS/NPP fails to meet the requirements and both MERIS and MODIS stop operating.

Recommendation: NASA and NOAA's current efforts to resolve international data access issues should continue and be given high priority. NASA, NOAA, and ESA should continue to include foreign scientists as part of their mission science teams to foster information and data exchange.

VIIRS/NPP Assessment

In 2007, the ocean color community articulated problems with the NPOESS' NPP VIIRS (Siegel and Yoder, 2007). Users were concerned about the ability of the VIIRS on NPP to deliver multi-spectral data of sufficient quality to sustain the time-series of oceanographic products derived from SeaWiFS and MODIS-Aqua. The community reached these conclusions based on an NPOESS Integrated Program Office (IPO) report regarding VIIRS on NPP laboratory performance tests. Optical cross-talk was of greatest concern.[1]

The community suggested two options to mitigate risk of a disruption of the ocean color data record:

> 1) Aggressively pursue and document improvements to the VIIRS sensor on NPP that enable it to meet the specifications required for climate capable ocean color observatories; or
>
> 2) Implement a stand-alone, global ocean color mission.
> (Siegel and Yoder, 2007)

The second option was not pursued. This study aims to assess whether improvements to the VIIRS sensor and mission that have been and continue to be made will allow VIIRS data to meet the requirements for climate-quality ocean color data.

As this report was being written, VIIRS/NPP was successfully integrated to the spacecraft; it now awaits launch. After integration with the spacecraft, NIST conducted full system tests of VIIRS radiometric performance. These tests included evaluation of relative spectral response (RSR), polarization sensitivity, and stray light characterization. These tests quantified VIIRS' non-compliance of integrated out-of-band (OOB) response and cross-talk among relevant ocean color spectral bands. Dynamic and static electrical

[1] Optical cross-talk is scattering of light from one band to another, caused by defects in the manufacturing of the VIIRS Integrated Filter Assembly (IFA).

and optical cross-talk was observed. Quantitative analysis of optical cross-talk is in progress. In parallel, Northrop Grumman Aerospace Systems (NGAS) proposed a data-processing correction method that is in government peer review. It is our expectation that the optical cross-talk that is a result of defects in the VIIRS Integrated Filter Assembly (IFA) will be corrected for the second VIIRS sensor. The hardware issue will remain in the VIIRS/NPP. The VIIRS/NPP optical cross-talk and OOB shortfalls compared with the VIIRS specification affect the performance of ocean color and aerosol observations.

Otherwise, the pre-launch VIIRS/NPP tests conducted by NIST indicate that the sensor meets SNR, dynamic range, linearity, uncertainty, stability, and polarization specifications (Turpie, 2010). Tests detected minor variances for gain transition, but gain transition points are well characterized. Tests also identified potential "striping." Striping, evident in MODIS Level 1a and 2 imagery, is typically seen in dark ocean scenes where small errors in detector gain and offset correction cause brightness variations from one detector to the next over a cross-track scan. Plans for post-launch striping correction similar to those applied to Landsat and MODIS data are in place if needed. Overall, VIIRS/NPP meets requirements for noise-equivalent radiance, dynamic range, gain transition, linearity, uniformity, absolute radiometric difference, and stability. Therefore, the VIIRS environmental data records (EDRs) are expected to meet Integrated Operational Requirements Document thresholds, with the possible exception of ocean color and aerosol optical depth.

Conclusion: Because of the VIIRS/NPP issues described above, the committee expects that deriving high-quality ocean color products from VIIRS/NPP is possible but will be challenging. The importance of vicarious calibration, stability monitoring, and a vigorous calibration/validation effort cannot be overstated and are discussed in more detail in Chapter 3.

In November 2010, the NPP project scientist told the committee:

> **We are optimistic that the [NPP] VIIRS instrument may still be a viable ocean color instrument, provided that the calibration and validation infrastructure of heritage NASA EOS missions is in place.** This infrastructure includes a plan and support for vicarious calibration site(s), a data/validation program, on-orbit calibration maneuvers, regular mission-level data reprocessing, and the use of NASA selected operational algorithms. The VIIRS on-orbit performance, due to the OOB calibration biases alone, should be no worse than SeaWiFS. If the VIIRS OOB calibration biases are not adversely complicated by the cross-talk, the heritage OOB mitigation approaches that were developed for SeaWiFS and MODIS-Aqua should work for VIIRS. These approaches use vicarious calibration as the primary correction for the OOB bias in the calibrated [top of atmosphere] TOA radiances, then use direct OOB corrections of the water-leaving radiances to remove residual OOB biases.
>
> (Presentation to NRC by J. Gleason, November 2010)

Although the committee is pleased that JPSS plans a vicarious calibration program to address ocean color issues on NPP VIIRS, it is critical that plans for vicarious calibration, as well as plans for routine reprocessing and stability monitoring, are in fact implemented.

As concluded in the previous chapter, a vicarious calibration is critical to overcoming some of the sensor's shortcomings and to ensure accuracy requirements for L_w are met. Currently, MOBY (or a MOBY-like approach) is the only proven and operational approach to undertake such a vicarious calibration. However, at the time that this report was completed, funding allocations for a MOBY-like vicarious calibration program were insufficient. The committee was not aware of any definitive plans to conduct a MOBY-like effort for VIIRS/NPP in the near term.

The committee heard arguments that, due to time pressure in delivering ocean color to the operational community quickly and the limited number of match-ups during the first year, the project office may rely more heavily on SeaWiFS[2] and MODIS data during the first year to set the gain factor.

It is true that during the first year obtaining enough match-ups to set the gain may be difficult (vicarious calibration for SeaWiFS over 13 years yielded 160 match-ups). Nonetheless, it remains imperative that MOBY be maintained until an alternative proven approach has been tested and deployed. A MOBY or a MOBY-like approach needs to be maintained continuously to develop the required dataset of match-ups. Indeed, because it takes many years and many vicarious calibration points to get down to 0.3 percent absolute accuracy, the vicarious calibration effort will yield high-quality products sooner if it begins immediately after launch.

Conclusion: Without a MOBY-like approach to vicarious calibration, the accuracy requirements of the climate research community cannot be met.

There is an overwhelming probability that a disruption in funding will result in the disbanding of the group with the technical and institutional memory to operate a system such as MOBY. To date, an appropriate alternative approach to conduct a vicarious calibration has not been demonstrated. Because NOAA is responsible for the calibration of VIIRS and for maintaining climate data records, NOAA is also responsible for maintaining the capability to conduct a vicarious calibration. Funding to maintain the proven vicarious calibration approach seems to be easily justified, considering the importance of the vicarious calibration to the overall success of the VIIRS/NPP mission, and the small cost of the program compared to the overall mission cost.

[2] These comments were made prior to the failure of SeaWiFS.

Conclusion: Based on experience with SeaWiFS and MODIS, a MOBY-like approach for a vicarious calibration is the proven method to meet the accuracy requirements for climate-quality data. Because of a funding shortage, VIIRS/NPP may use MODIS for the vicarious calibration during the first year, primarily for operational applications. However, this approach does not meet the accuracy requirements listed in the previous chapter.

Conclusion: Based on NIST's most recent and thorough instrument characterization, the VIIRS sensor on NPP continues to have problems with the filter cross-talk and out-of-band response. The approach with the best chance for obtaining ocean color CDRs from VIIRS/NPP is to implement a vicarious calibration program based on MOBY match-ups and to monitor sensor stability with a monthly lunar look.

Conclusion: If it is NOAA's goal to produce climate-quality ocean color data from VIIRS/NPP, NOAA funding for the vicarious calibration needs to be sufficient to support the current level of MOBY operations and the development and deployment of a replacement unit.

VIIRS is patterned after MODIS, with an improved solar diffuser design based on lessons learned from MODIS-Terra. In addition to providing deep space and lunar views available roughly quarterly without spacecraft maneuvers, VIIRS also contains the MODIS-derived solar diffuser stability monitor. However, the experience with MERIS demonstrates that the stability of the solar diffuser needs to be monitored, and this ability depends on how well the stability monitor on VIIRS will perform. The SeaWiFS and MODIS experiences indicate that monthly lunar looks will be required despite the solar diffuser and stability monitor, because instrument degradation is not always predictable. Furthermore, vicarious calibration cannot be used to determine the rate of degradation of the atmospheric correction bands, because the water-leaving radiance signal is so low at those wavelengths. Thus, the only option for VIIRS to monitor degradation in those bands is with a lunar look. A presentation to the committee by Fred Patt stated VIIRS will image the moon three to four times a year with no maneuvering of the spacecraft. This does not meet the requirement of monthly sampling frequency. Patt also stated that small roll maneuvers (fewer than 15 degrees) are required to acquire eight to nine additional lunar calibration views per year (Patt VIIRS ATBD document). If implemented these roll maneuvers would increase the number of lunar views to the required monthly frequency. At the time this report was prepared, no final decision had been made whether to implement roll maneuvers. However, the original instructions were to not implement roll maneuvers.

Conclusion: VIIRS/NPP is currently scheduled to collect four lunar looks per year, which is insufficient to meet the requirement. To monitor the sensor degradation, a 15-degree roll maneuver of the spacecraft eight to nine times a year would be sufficient to meet the requirement of obtaining monthly lunar looks.

Recommendation: JPSS should conduct spacecraft maneuvers to collect monthly lunar looks for VIIRS/NPP.

The Sensor Intercomparison and Merger for Biological and Interdisciplinary Oceanic Studies (SIMBIOS) program has contributed to the success of the SeaWiFS and MODIS missions. The SIMBIOS program led the effort to validate the ocean color products. Besides calibrating the sensor with solar and lunar views and MOBY match-ups, it collected and archived a global dataset of in situ data to ground-truth the satellite products. In addition, the program was very successful in developing working relationships with the international community and foreign space agencies (McClain, 2010).

Although plans presented to the committee for calibration and validation included all necessary elements, the funding to support these efforts for VIIRS/NPP was not available. In addition, the plans were relatively limited in scope and lacked details to ensure a successful implementation. They appeared limited to U.S. coastal waters. Considering the fast-approaching launch date of the VIIRS sensor, the committee concludes that a high level of uncertainty remains regarding the availability of a high-quality calibration and validation program such as the SIMBIOS program.

The committee is most concerned about the current uncertainty regarding the timing and level of NOAA's financial support for a MOBY-type vicarious calibration program (DiGiacomo and Guenther, personal communication), as well as NOAA's apparent lack of commitment and capability to reprocess the VIIRS data (NOAA, 2010). Both are absolutely essential if VIIRS is to produce climate- and science-quality data. These concerns were echoed by all workshop and meeting participants throughout the study period and had not been resolved at the time this report was concluded (sixth months prior to launch date).

NOAA plans to process, archive, and distribute VIIRS data. However, based on its report to the committee (NOAA, 2010), NOAA does not have (nor has it demonstrated) the technical and infrastructure capabilities to do end-to-end processing and reprocessing of ocean color data.

Moreover, reprocessing of the data is not included in the data management plans contemplated for VIIRS/NPP. Reprocessing of data is required for the development of climate-quality data records. In addition, NOAA has not yet developed the mechanisms to engage experts in the academic and international community to provide feedback and revise algorithms and methods for product development. NOAA has recognized this deficiency and is attempting to develop the in-house capacity for end-to-end data processing (NOAA, 2010). However, the current management structure of JPSS (separate from NOAA/National Environmental

Satellite, Data, and Information Service [NESDIS] presents an additional challenge to NOAA to implement the agency's own recommendations (NOAA, 2010).

The NASA Ocean Color Group has the expertise and resources to do end-to-end processing of VIIRS data. NASA is capable of developing a processing system by launch, and VIIRS ocean color products would be processed and available through mechanisms that are familiar to the research and operational community. Further, as of today, no module exists to provide access to Level 3 data from VIIRS/NPP. The NASA Ocean Color Group has built such modules for SeaWiFS, MODIS, and MERIS. It has a code in place to bin VIIRS data to Level 3 and the expertise to make the module available for VIIRS/NPP data. To build its own in-house capacity for end-to-end processing, NOAA is well advised to engage NASA to enable the knowledge transfer (NOAA, 2010).

Conclusion: NOAA is responsible for data management of VIIRS ocean color products for the nation but has not yet demonstrated that it has the required expertise or infrastructure to successfully achieve this task. The NASA Ocean Color Group does not have the funding to process, reprocess, and distribute VIIRS data, but has the unique expertise and infrastructure. Contracting the NASA Ocean Color Group to manage VIIRS/NPP data is the only option for the foreseeable future to ensure high-quality management of VIIRS data. NOAA and NASA should work together to shift this capability to NOAA as soon as possible, or they should develop a partnership for ocean color processing that serves the missions of both agencies.

Conclusion: As of now, the following requirements are not met for VIIRS/NPP:

- ***Stability monitoring;***
- ***Data processing, reprocessing and distribution;***
- ***Vicarious Calibration program;***
- ***Global validation program throughout the life span of the mission; and***
- ***Algorithm development and research.***

Conclusion: The VIIRS sensor on NPP continues to have problems with the filter cross-talk and out-of-band response. It remains to be seen whether optical cross-talk issues can be overcome on orbit via software corrections. VIIRS on NPP has the potential to meet requirements only if a vicarious calibration is undertaken and the sensor stability is monitored with a monthly lunar viewing.

Recommendation: If VIIRS/NPP is to continue to provide SeaWiFS/MODIS-quality ocean color data, NOAA should immediately implement the following:

- ***spacecraft maneuvers throughout the life of the mission to provide monthly lunar looks to quantify sensor stability;***
- ***fund MOBY and a new MOBY-like program to replace the aging MOBY; and***
- ***a capability equivalent to the NASA Ocean Color Group to process, reprocess, and distribute VIIRS data in a manner consistent with the heritage missions (CZCS, SeaWiFS, and MODIS).***

Conclusion: NOAA's ocean color mission would benefit from engaging the NASA Ocean Color Group at Goddard Space Flight Center to process, archive, distribute, and reprocess NPP/VIIRS data in the near term. Initially, this could be accomplished through subcontracting its services, although this is not a long-term solution.

An option to ensure the availability of a capacity equivalent to NASA's Ocean Color Group is to contract with that group. Such a contract should include but not be restricted to these tasks:

- process, reprocess, distribute the data, and generate new and improved products;
- work with the VIIRS calibration team to assess trends in sensor performance and to evaluate anomalies;
- implement a process to engage experts in the field of ocean color research to revisit standard algorithms and products, including those for atmospheric correction, to ensure consistency with heritage instruments and for implementing improvements; and
- form a data product team to work closely with the calibration and validation teams to implement vicarious and lunar calibrations, expand global validation efforts and provide oversight of reprocessing.

Recommendation: NOAA should extend the validation program to cover the full range of global ocean conditions.

ENSURING GLOBAL HIGH-QUALITY OCEAN COLOR DATA FOR THE NEXT FIVE TO TEN YEARS

While the most immediate need and highest priority is to ensure that the VIIRS/NPP mission is of highest quality possible, some near-term missions also hold great promise. The most promising are two foreign missions. The third mission we consider here is the second VIIRS sensor, to be launched as part of the JPSS1 mission.

Sentinel Mission

ESA is developing an operational mission as part of its Global Monitoring for Environment and Security (GMES) program. Because the Sentinel mission is operational, the requirements for revisit, coverage, and mission life cycle are stringent. Two OLCIs are being built as part of this program; the first OLCI (3A) is to be launched in April 2013. The design follows MERIS with a dual Spectralon solar diffuser stability monitoring system and deep space looks. The committee hopes this will include a vicarious calibration of sensor gains, as is being done now for MERIS. The OLCI comprises five independent narrow field-of-view cameras arranged in a fan configuration to offer a total 68.5-degree field-of-view, tilted 12.5 degrees off-nadir to avoid sun glint. It will have 21 spectral channels compared to the 15 on MERIS. Based on the quality of the MERIS mission and the design features of these sensors, data likely will be of high quality, especially because climate research is one of its main applications. This assumes that a vicarious calibration will be pursued as has been recently done for MERIS. However as with MERIS, questions regarding data access will need to be resolved before Sentinel will fully satisfy the requirements of U.S. resource managers and scientists.

Conclusion: The Sentinel sensor and mission description are promising, but data access needs to be resolved.

S-GLI/GCOM-C1 and GCOM-C2

The Japanese Global Change Observation Mission (GCOM) also plans to launch two ocean color sensors for climate monitoring purposes. As discussed, this goal is associated with stringent mission and sensor requirements. To monitor the sensor's stability, the SGLI Visible and Near-Infrared Radiometer (VNR) offers a Spectralon solar diffuser, internal light-emitting diodes (LED) sources, and deep space views. With planned satellite maneuvers, lunar looks also are anticipated. The sensor will have 19 wavebands (375 to 12,500 nm) and a spatial resolution of 250 m, with the goal to improve coastal and aerosol observations. Following an initial evaluation period, the data products are likely to be openly available, as was the case for OCTS and GLI, although it is not yet clear if near-real time access will be an option for U.S. coastal waters.

Conclusion: Based on the sensor and mission description and operation for S-GLI, and given past history with data access to OCTS, S-GLI could meet all requirements and be an excellent Type 1 and 2 sensor.

VIIRS/JPSS1 and JPSS2

Because VIIRS/NPP was designed as the preparatory mission for the operational program, lessons from VIIRS/NPP should be applied to VIIRS/JPSS1 to ensure improvements are made. The VIIRS sensor on the JPSS1 mission needs to include an improved filter array to avoid the cross-talk problems associated with VIIRS on NPP. As discussed in the previous section, many issues remain regarding the overall mission planning and design, including stability monitoring, vicarious calibration based on a MOBY-like standard, pre-launch characterization, and data validation/calibration and processing/reprocessing.

Based on what we have learned to date, all recommendations for VIIRS on NPP need to be implemented for VIIRS/JPSS1, in particular:

- Stability monitoring;
- Vicarious calibration based on a MOBY-like approach;
- Pre-launch characterization of VIIRS/NPP applied to all follow-on missions; and
- Processing, reprocessing, and distribution (for details see Chapter 5).

If the problems with the first VIIRS can be avoided during the JPSS phase, these follow-on missions can deliver climate-quality ocean color data.

PACE and ACE

ACE is one of NASA's Decadal Survey missions and would include an advanced ocean color capability to serve the research community. PACE was announced in 2010 as part of NASA's Climate Initiative and is an advanced ocean color imager with requirements similar to those planned for ACE. Very little information about PACE or ACE was available to the committee. Based on a draft document provided by C.R. McClain (NASA's GSFC), the ocean color radiometry requirements for ACE (and presumably for PACE) are given below. The requirements are stringent; if they are met, PACE and ACE would satisfy many of the ocean color needs of the research community discussed in Chapter 5.

The ocean radiometer requirements are outlined below. The first list provides general sensor performance and mission support requirements. Table 4.6 provides specific data on multispectral bands, bandwidths, typical clear sky TOA radiances over the ocean, saturation radiances, and minimum SNRs (based on the analyses above). In Table 4.6, the SNR value at 350 nm is lower than in the other UV bands because its application for detecting absorbing aerosols does not require a value of 1,000 nm. Also, the SNR at 678 nm is set at 1,400 nm based on analysis of MODIS retrievals (the bio-optical sensitivity analyses above did not include fluorescence line height). In the wavelength domain of 345-755 nm, multispectral bands are aggregations of 5-nm hyperspectral bands.

Below are general requirements for ocean radiometer and mission support:

Radiometer Spectral Attributes

- 26 multispectral bands (Table 4.6) including:
  - o 10-nm fluorescence bands (667-, 678-, 710-, and 748-nm band centers)
  - o 10- to 40-nm bandwidth aerosol correction bands at 748, 765, 865, 1,245, 1,640, and 2,135 nm
  - o 820-nm band for estimation of column water vapor concentration
  - o 350-nm band for absorbing aerosol detection
- 5 nm resolution 345 to 755 nm (functional group derivative analyses)
- Polarization: <1.0 percent sensor radiometric sensitivity, 0.2 percent pre-launch characterization accuracy
- No saturation in multispectral bands

Accuracy and Stability

- <2 percent pre-launch radiance calibration accuracy
- On-orbit vicarious calibration accuracy to 0.2 percent
- 0.1 percent radiometric stability knowledge (mission duration)
- 0.1 percent radiometric stability (1-month pre-launch verification)

Spatial Coverage

- Two-day global coverage (58.3-degree cross-track scanning)
- 1-km resolution at center of swath

Other

- Sensor tilt (±20 degree) for sun-glint avoidance
- Five-year minimum design lifetime
- Monthly lunar imaging at 7-degree phase angle through Earth-view sensor port

TABLE 4.6 OES Multispectral Band Centers, Bandwidths, Typical TOA Clear Sky Ocean Radiances (L_{typ}), Saturation Radiances (L_{max}), and Minimum SNRs at L_{typ}

λ	Δλ	L_{typ}	L_{max}	SNR-spec
350	15	7.46	35.6	300
360	15	7.22	37.6	1,000
385	15	6.11	38.1	1,000
412	15	7.86	60.2	1,000
425	15	6.95	58.5	1,000
443	15	7.02	66.4	1,000
460	15	6.83	72.4	1,000
475	15	6.19	72.2	1,000
490	15	5.31	68.6	1,000
510	15	4.58	66.3	1,000
532	15	3.92	65.1	1,000
555	15	3.39	64.3	1,000
583	15	2.81	62.4	1,000
617	15	2.19	58.2	1,000
640	10	1.90	56.4	1,000
655	15	1.67	53.5	1,000
665	10	1.60	53.6	1,000
678	10	1.45	51.9	1,400
710	15	1.19	48.9	1,000
748	10	0.93	44.7	600
765	40	0.83	43.0	600
820	15	0.59	39.3	600
865	40	0.45	33.3	600
1,245	20	0.088	15.8	250
1,640	40	0.029	8.2	250
2,135	50	0.008	2.2	100

Radiance units are mW/cm^2 μm str.

CONCLUSIONS

To date, MODIS-Aqua is the only sensor in orbit that meets all requirements for sustaining climate-quality water-leaving radiances and ocean color products for U.S. scientists. MERIS data access is much improved, and as of March 2011, discussions are under way between NASA and ESA for a bulk data exchange to include MERIS Level 1B data. Experts at NASA/GSFC believe that Level 1B data is a realistic substitute for access to Level 0 data. Data access (as discussed below) is a potential issue with almost every foreign sensor, especially with proprietary sensor design information.

Until PACE is launched (currently planned for 2019), the VIIRS series on NPP and JPSS1 will be the only U.S. ocean color sensors in orbit that are not beyond their design life spans (e.g., MODIS-Aqua). If the appropriate steps are not taken now to ensure that all requirements are met for a successful mission, U.S. scientists will not have access to a research/climate-quality dataset for ocean color from U.S. sensors. In addition, U.S. resource managers, for example those at NOAA's NMFS and National Ocean Service (NOS) and at state and local agencies, will not have access to operational products in near-real time.

Recommendation: To mitigate the risk of a data gap, NOAA should ensure that VIIRS meets all requirements for a successful mission, including:

- ***Stability monitoring;***
- ***Vicarious calibration based on a MOBY-like approach;***
- ***Pre-launch characterization;***
- ***Global validation program throughout the life span of the mission; and***
- ***Processing, reprocessing, and distribution of the data.***

At the moment, two sensors (MODIS and MERIS) are providing ocean color data at the same time. This redundancy has served the climate research community well because it has enabled scientists to intercalibrate the sensors and improve the reprocessing to ensure data continuity. However, the sensors are beyond their anticipated life spans. SeaWiFS recently stopped delivering data and has been terminated. It is uncertain how much longer the other two sensors can deliver high-quality observations. Therefore, it is plausible that, should MODIS and MERIS sensors fail, OCM-2 will be the only new sensor in space before VIIRS on NPP is launched. In addition, it is likely that OCM-2 and VIIRS/NPP will be the only Type 1 and 2 ocean color missions in orbit before Sentinel-3A is launched in 2013.

Conclusion: Because OCM-2 and VIIRS could be the only sensors in orbit until launch of Sentinel-3A in 2013, access to data from OCM-2 is a high priority for U.S. scientists. The committee notes that neither NOAA nor NASA is aggressively pursuing routine access to OCM-2 ocean color data for U.S. users, although preliminary discussion is ongoing and an MOU is in place.

The timeline of current and future ocean color sensors shown in Figure 4.1 does not necessarily represent the current and future availability of ocean color data, because several of the sensors have unusable and/or inaccessible data. For example, as a result of uncertainties and instabilities in the pre-launch and on-orbit characterization of MODIS-Terra, these data have been largely unusable (Franz et al., 2008). The data from India's OCM sensor has generally not been available to the international community (Wilson, 2011), and there also are serious issues with its calibration (Lyon, 2009). It is anticipated that data from OCM-2 will be more accessible to the international community, but this remains to be seen. However, the OCM-2 is primarily a regional-scale mission intended for the Indian fishing community, not as a global mission.

Although Level 1-3 MERIS data are available to U.S. scientists, access to Level 0 data remains an issue (Wilson, 2011). While most data users only desire access to Level 1-3 data, some space-agency projects working with multiple international satellite datasets and with access to multiple sources of calibration data want access to Level 0 data, or to an appropriate substitute (Level 1B in the case of MERIS). The Level 0 data (or its substitute) are needed so users can go through identical data processing steps for different sensors. Not having access to Level 0 data has been a source of contention in the past. It might also become an issue when attempting to develop an international merged ocean color dataset—as is proposed for the virtual constellation—that requires access to all data/metadata for reprocessing and merging (see discussion in Chapter 5). International Traffic in Arms Regulations (ITAR) restrictions may force limits to the distribution of VIIRS Level 0 data that may contribute to friction between national satellite projects and present a barrier to full international cooperation for ocean color data processing.

Conclusion: Data access is a major issue that needs to be resolved before many of the sensors listed in Table 4.4 meet requirements.

NASA and NOAA have good relations with ESA and JAXA and a longstanding tradition of exchanging satellite data. Relations with ISRO for data exchange are evolving in a positive way.

Nevertheless, issues arise with all partners on the details of data access. For example, there are generally few if any restrictions related to the exchange of Level 3 data products, once the mission teams have established confidence in the quality of the products. However, Level 0 and Level 1 data present problems. Issues related to data volume, proprietary software, ITAR restrictions (for VIIRS), etc. make it more difficult for U.S. and foreign agencies to exchange complete Level 0 or Level 1 datasets. These issues also can impede the full exchange of information on calibration, characterization, and processing details. When merging data from multiple sensors, it is impossible to generate climate-quality data products without full access to Level 0 and Level 1 datasets and without complete information on calibration, characterization, and processing details.

In addition, these data exchange issues can make it difficult for U.S. ground stations to downlink raw data from non-U.S. sensors for U.S. coastal waters. Without direct downlink capability to U.S. ground stations, it is extremely difficult, if not impossible, to generate true real-time products for applications for the United States.

In recognition of these challenges, the international Committee on Earth Observation Satellites[3] (CEOS) has formed several "virtual constellations," including the Ocean Colour Radiometry Virtual Constellation (OCR-VC). Chapter 5 discusses in greater detail how this virtual constellation presents unique opportunities to overcome some of these challenges.

[3] http://www.ceos.org/.

5

Advancing Global Ocean Color Remote Sensing into the Future

Ocean color observations from satellites are the principal tool for the synoptic global monitoring of marine ecosystems. It is imperative that ocean color observations are sustained and enhanced into the future. These observations serve the expanding needs of the scientific user community as it seeks to understand long-term trends in marine ecosystems and their interactions with the global carbon cycle. In turn, managers apply this new knowledge to value and manage marine resources. This means that future sensors and algorithms need to be enhanced to support an increasing diversity of ocean color products and applications. However, creating long time-series remains a major challenge, one that is not unique to ocean color remote sensing (NRC, 2004b, 2008b). These challenges and approaches for sustaining long-term ocean color remote sensing are explored in this chapter. The key requirements include planning to ensure continuity and overlap among sensors; building and maintaining the human capital to process, reprocess, and use ocean color products for research; and building international coordination and cooperation.

Although the study task focuses on data continuity, it is important to note that continuity and advancements in the science require far more than simply sustaining SeaWiFS/MODIS-type measurements. Many applications listed in Chapter 2 require more advanced remote sensing capabilities. This chapter, therefore, explores options for enhancing ocean color research products. In addition, the U.S. academic research community, which is primarily funded by National Aeronautics and Space Administration (NASA), needs ocean color instruments such as Aerosol-Cloud-Ecosystems (ACE) and the Pre-Aerosol-Clouds-Ecosystems (PACE) for new and improved applications such as those described in a recent NASA report and summarized below.

ENHANCEMENTS FOR THE FUTURE

Advancing Ocean Biology and Biogeochemistry Research

In 2007, the ocean biology and biogeochemistry research community completed a consensus document that laid out four priority science questions for the NASA Ocean Biology and Biogeochemistry program (NASA, 2007). These questions are:

- How are ocean ecosystems and the biodiversity they support influenced by climate and environmental variability and change, and how will these changes occur over time?
- How do carbon and other elements transition between various reservoirs in the ocean and Earth system, and how do biogeochemical fluxes impact the ocean and Earth's climate over time?
- How (and why) is the diversity and geographical distribution of coastal marine habitats changing, and what are the implications for the well-being of human society?
- How do hazards and pollutants impact the hydrography and biology of the coastal zone? How do they affect us, and can we mitigate their effects?

The implementation strategy calls for a mix of new sensors including:

1. a global hyperspectral imager that would be an advanced Type 1/Type 2 sensor with capabilities as envisioned for ACE and PACE;
2. a Multi-Spectral High Spatial Resolution Imager similar to Hyperspectral Infrared Imager (HyspIRI);
3. an ocean color sensor in geostationary orbit to focus on coastal and ocean processes that require multiple observations during a single day to resolve changes on short time scales (like Geostationary Coastal and Air Pollution Events [GEOCAPE]); and

4. a space-borne LIght Detection And Ranging (LIDAR) for improved atmospheric correction and oceanographic measurements, as is also planned for ACE (NASA, 2007).

Both the NASA Ocean Biology and Biochemistry (OBB) program and the National Research Council's (NRC) decadal survey plans call for a mix of ocean color satellite mission types that would help ocean scientists answer the high-level science questions they now face.

Global Hyperspectral Imaging Radiometer

Answering the first two priority science questions above will require the development of advanced global remote sensing capabilities. The planned NASA missions PACE/ACE will provide some of these new capabilities, including:

- Ultraviolet (UV) bands to improve the separation of chlorophyll and color dissolved organic matter (CDOM) absorption and thus significantly improved accuracy of both products. This capability is especially important because of projected changes in the ocean due to rising temperatures and ocean acidification.
- Short wave infrared (SWIR) bands (1,200-1,700 nm) demonstrated by Moderate Resolution Imaging Spectroradiometer (MODIS), which in that case led to improved atmospheric correction over turbid coastal waters, in comparison to what was achieved with Sea-viewing Wide Field-of-view Sensor (SeaWiFS).
- Additional bands in the UV that would help correct for absorbing aerosols, a major source of uncertainty for the present generation of ocean color sensors particularly in coastal waters, and a specific UV band at 317.5 nm that would provide simultaneous ozone corrections.
- Improved atmospheric correction by determining aerosol altitude and type using a profiling LIDAR, advanced polarimeter, or both as envisioned for ACE.

With these capabilities, it will be possible to separate phytoplankton functional groups such as carbon exporters (diatoms), nitrogen fixers (*Trichodesmium sp.*), calcium carbonate producers (coccolithophores), and the microbial loop organisms (*Prochlorococcus sp.*). It also will be possible to enable derivation and optimization of fluorescence retrievals, which are particularly beneficial in quantifying phytoplankton chlorophyll biomass during phytoplankton blooms and in coastal waters.

Conclusion: Advanced ocean color remote sensing capabilities are central to answering questions related to changing conditions in the marine ecosystem and biogeochemical cycles due to climate change.

Multi-Spectral High Spatial Resolution Imaging

Many coastal applications—such as monitoring for Harmful Algal Blooms (HABs), ecosystem-based fisheries management, and research on benthic habitats including coral reefs and coastal wetlands—require greater spatial resolution and additional spectral bands than are currently available from most satellites to resolve the complex optical signals that coastal waters produce. These measurements historically have been made from airborne sensors, usually flown by airplanes over a particular region. Airborne hyperspectral observations are well suited for routine studies of localized areas (e.g., coral reefs, seagrass beds) and for episodic events (e.g., HABs, oil spills) that require high spatial or spectral resolution, or on-demand repeat times. The technology is well proven for mapping shallow-water bathymetry and bottom type (e.g., Mobley et al., 2005; Dekker et al., in press), mapping and monitoring coral reefs (Hochberg and Atkinson, 2003; Lesser and Mobley, 2007), and detection of oil spills (Lennon et al., 2006). For example, the Airborne Visible and InfraRed Imaging Spectrometer[1] (AVIRIS), developed by the Jet Propulsion Laboratory (JPL), made many flights over the Deepwater Horizon BP oil spill site.[2] The hyperspectral information enabled researchers to map out the oil spill location and thickness. In addition, JPL is supporting the construction of a portable hyperspectral imager (i.e., the Portable Remote Imaging SpectroMeter [PRISM][3]).

Although the capability has been built and demonstrated, past applications of this hyperspectral technology have been limited to short surveys yielding single snapshots of a given coastal region. Routine and sustained surveys of the U.S. coastal waters are not undertaken because it is difficult to find the necessary funding to routinely fly these airborne systems. Other countries, Australia and the People's Republic of China in particular, have invested heavily in airborne hyperspectral imaging systems and routinely employ them in studies of their coastal and inland waters. The United States also would benefit greatly from dedicated and adequate support for airborne hyperspectral imaging systems that could be used for routine observations of coastal waters or to respond to episodic events as needed.

High spatial resolution, hyperspectral measurements also can be made from satellite missions and were recommended as part of the Decadal Survey (NRC, 2007). Airborne missions that gather such measurements provide them on an intermittent basis. Satellite hyperspectral remote sensing would make these observations routine and allow sustained application of the data for HAB detection, oil spill monitoring, shallow benthic habitat characterization, and other research and research management applications.

[1] See http://aviris.jpl.nasa.gov/.

[2] See http://www.jpl.nasa.gov/news/news.cfm?release=2010-184; accessed February 8, 2011.

[3] See http://airbornescience.jpl.nasa.gov/prism/.

Satellite hyperspectral remote sensing mission was piloted with the Hyperion EO-1 mission.[4] The EO-1 satellite was launched in fall 2000 to demonstrate the technology for the Landsat Data Continuity Mission. Because of the satellite's success, the research community successfully advocated to continue the image acquisition from EO-1. Data from the hyperspectral satellite SCanning Imaging Absorption spectroMeter for Atmospheric CartograpHY (SCIAMACHY), a European sensor designed to measure various trace gases, aerosols and clouds, also are used for deriving ocean color measurements and have been applied to distinguish phytoplankton groups (Bracher et al., 2009).

In addition, the Hyperspectral Imager for the Coastal Ocean (HICO;[5] Lewis et al., 2009; Davis et al., 2010) was developed by the Office of Naval Research and installed on the International Space Station in late 2009. Because of mission constraints of the International Space Station, HICO currently collects only one image per orbit of selected targets, but with good results. Although unable to provide global or highly accurate data, HICO is well suited for certain applications that require high spatial or spectral data in coastal waters during a limited period. HICO collects hyperspectral imagery (380-1,000 nm by 5.7 nm bandwidth) at ~100 m spatial resolution. Its primary applications are retrieval of coastal optical properties, bathymetry, bottom classification, and water inherent optical properties (IOP), along with terrain and vegetation maps. Nevertheless, data availability to the community is minimal.

Plans also are under way for a global hyperspectral mission, the HyspIRI,[6] as outlined by the Decadal Survey (NRC, 2007). HyspIRI is a Tier 2 mission in the Decadal Survey, which NASA plans to launch after 2020 (NASA, 2010). The goal of the HyspIRI mission, which is currently in the study stage, is to detect ecosystem changes due to climate change and human impacts on land and in the ocean. HyspIRI will make hyperspectral observations of radiance from 380 to 2,500 nm at 10-nm resolution with a 60-m pixel at nadir. It will also be configured with a multispectral thermal IR imager. The temporal revisit times are ~3 weeks for the visible/SWIR instrument and a one-week revisit for the thermal IR sensor. Besides looking at ecosystem changes, HyspIRI will be able to map surface rock, soil, and snow composition. Because it samples a fixed location in the global ocean only once every three weeks, HyspIRI's ability to measure change in fast-moving planktonic communities is limited and not as useful for characterizing pelagic ocean conditions. The high spatial and spectral features of the sensor will be used to assess coastal habitats on global and seasonal scales, particularly benthic features such as corals, seagrasses, and kelp.

[4] See http://eo1.gsfc.nasa.gov/.

[5] See http://hico.coas.oregonstate.edu; accessed May19, 2011.

[6] See http://hyspiri.jpl.nasa.gov.

Conclusion: Almost all coastal research and operational applications require ocean color remote sensing capabilities that are not routinely available. To sustain and advance these coastal applications, a high spectral and high spatial resolution sensor is required.

Geostationary Radiometers and Geostationary Hyperspectral Imaging Radiometers (Type 4 sensors)

All current sensors except for the South Korean sensor Geostationary Ocean Color Imager (GOCI) are in polar orbit (see Chapter 4). South Korea launched the first geostationary ocean color sensor in June 2010 (Table 5.1). Although the limited geographic scope of this satellite makes it less relevant to the U.S. research and operational community, access to these data would be valuable for developing future geostationary missions in the United States. Initial Korean plans called for open data access in 2011.

Although the current systems in polar orbit can provide global data coverage once every day or two, they offer only coarse spatial resolution. The resulting lack of data with high spatial and temporal sampling frequency was recognized many years ago. Although near-daily data may be adequate for climate data records from the open ocean (assuming data comparability from different sensing systems), daily acquisition is inadequate for critical coastal operational and research applications. Coastal waters and shorelines exhibit significant diurnal variability. A single geostationary earth orbit (GEO) instrument could provide near-hourly data updates for the continental U.S. coasts, as required to properly characterize important changes in coastal marine environments. For example, water clarity, tidal variability of shoreline and estuaries, effluent discharge, diffusion and absorption, and other parameters must be tracked frequently (IOCCG, 2008). Because many space agencies are interested in and have plans for geostationary ocean color satellites, a new International Ocean Colour Coordinating Group (IOCCG) working group was formed to address requirements, advocate for coordination, and foster collaboration.

Two U.S. options exist for increasing the supply of ocean color data from sensors in geostationary orbit. First, a geostationary ocean color sensor hosted on a commercial satellite could be a cost-effective choice to obtain coastal high-resolution or hyperspectral ocean color radiance (for details see Appendix D). A second option is the GEOCAPE mission. The Earth Science Decadal Survey (NRC, 2007) recommended GEOCAPE as a Tier 2 mission, which NASA plans to launch after 2020 (NASA, 2010). This mission would focus on retrievals of tropospheric trace gases and aerosols and coastal ocean color from a geostationary spacecraft. Although an ocean color GEOCAPE would be optimized for coastal observation, its orbit also allows for observations of offshore waters. This capability could support research cruises within the covered area. Because GEOCAPE would be able to dwell over any area, it could

TABLE 5.1 Current and Planned Type 4 Sensors (geostationary)

Sensor/Satellite	Agency	Launch Date	Swath	Resolution	Bands	Spectral Coverage (nm)
GOCI/COMS	KARI/KORDI (S. Korea)	2010	2,500	500	8	400-865
GOCI-II/KMGS-B	KARI/KORDI (S. Korea)	2018	1,200 × 1,500 TBD	250/1,000	13	412-1,240 TBD
GEOCAPE	NASA (USA)	After 2020		300 m	Hyperspectral at 10 nm	

be used to cross-calibrate radiances measured by different ocean color satellites in polar orbit.

NASA has initiated plans and science and engineering studies to equip GEOCAPE with the high spatial and temporal resolution required for coastal research.[7] The capabilities of the geostationary ocean color sensor include: multiple sampling per day of continental U.S. coastal waters and Great Lakes, 300- to 375-m spatial resolution and hyperspectral resolution (with capability of binning spectral bands), broad spectral coverage including UV-visible spectrum (VIS), near-infrared (NIR), and SWIR bands, high signal-to-noise ratio (SNR) and dynamic range, cloud avoidance, minimal polarization sensitivity (<0.2 percent), minimal stray light, narrow field-of-view (FOV) optics, low scatter gratings (<0.1 percent), no image striping or latency, and the capability of performing solar and lunar on-orbit calibration.[8]

Conclusion: The availability of a geostationary satellite would give federal agencies concerned with the degradation of coastal habitats the necessary capabilities to monitor the near-shore environment.

Active Remote Sensing—LIDAR—to Measure the Ocean's Scattering Properties and Phytoplankton Variable Fluorescence

Vertical changes in light-scattering properties measured through the atmosphere and into the ocean from a space-based LIDAR[9] can provide important new information for solving major ocean carbon and biogeochemistry science questions. Future missions that use measurements of water-leaving radiances to retrieve geophysical parameters related to ocean elemental cycles depend on accurate atmospheric corrections. This requires a strict accounting for the contribution of absorbing aerosols to top of the atmosphere (TOA) radiances, including information on their vertical distributions and total optical thickness. LIDAR measurements, both ground-based (e.g., Micropulse) and space-based (e.g., Geoscience Laser Altimeter System [GLAS]), can provide information on vertical aerosol structure at a resolution well beyond what's required for ocean applications (<0.5 km). LIDAR aerosol profiling measurements, simultaneous with passive radiometric data, will enable unsurpassed atmospheric corrections that will result in vastly improved ocean geophysical parameters. This capability is currently available from CALIPSO (Cloud-Aerosol LIDAR and Infrared Pathfinder Satellite Observation) and is planned for the ACE mission.

In addition to aerosol assessments, LIDAR remote sensing can measure the ocean's light-scattering properties independent of passive radiometer observations. Measures of LIDAR light scattering are related to particulate concentrations in the mixed layer (e.g., Churnside et al., 1998). Airborne LIDAR have been used for some time to demonstrate the ability to make profiles of light scattering at 532 nm and 355 nm into the water column (Wright et al., 2001). Most recently, this technique has also been applied to LIDAR measurements from space with data from CALIPSO (Hu, 2009). Radiative transfer modeling and observational data indicate that with an 100-m eye-safe Nd:Yg laser at an altitude of 600 km, sufficient subsurface scattering values can be retrieved to >15 m in clear ocean waters and to 5 m in turbid coastal waters. To cover this full range of optical conditions, space-based measurements will require 1 to 2-m vertical resolution and a LIDAR angle of incidence of 15 degrees relative to nadir (to avoid detector saturation at the surface). However, LIDAR will not provide global coverage and thus will benefit from simultaneous passive remote sensing to obtain the global coverage.

LIDAR also could enable the measurement of the photosynthetic rate and the physiological state of phytoplankton. LIDAR-based fluorescence has advantages over passive, solar-stimulated fluorescence (such as implemented on MODIS and described previously). This is because the laser source provides a consistent input of radiance and the changes can be measured over very short time periods, enabling the determination of variable fluorescence. Changes in variable fluorescence appear to behave in a consistent manner under a variety of environmental conditions, although a few stresses create unique behaviors. One of these conditions is iron-limited growth in the presence of high macronutrient concentrations. However, techniques

[7] See http://geo-cape.larc.nasa.gov/.
[8] See http://oceancolor.gsfc.nasa.gov/DOCS/.
[9] LIDAR refers to a technology that measures the property of a target by illuminating it with light and detecting the reflected light.

have been developed to distinguish these iron-limited regions from iron-replete areas (e.g., Behrenfeld and Kolber, 1999; Behrenfeld et al., 2009). Therefore, remote sensing assessments of the variable fluorescence can provide a means for globally defining HNLC conditions, monitoring temporal shifts in physiological province boundaries, and establishing functional links between new iron inputs (e.g., dust deposition events) and ecosystem responses.

Phytoplankton fluorescence kinetics has been measured in the field for more than 20 years and, through NASA support, has been successfully measured from aircraft (Chekalyuk et al., 2000). The "pump and probe" technique employed for these airborne tests will need to be modified for space-based applications to reduce LIDAR energy demands and to meet eye safety requirements. Technological solutions for these issues are under development.

Globally defining and monitoring physiological provinces through satellite variable fluorescence measurements will require aggregation of multiple LIDAR returns to improve signal to noise ratios. Measurements are needed at midnight and at dawn to determine maximal variable fluorescence and the relative nocturnal percentage decrease in variable fluorescence (both critical diagnostics). This approach would require two satellites and would also provide information on the degree of midday light inhibition of photosynthetic electron transport. The excitation laser wavelength must penetrate a wide range of ocean waters (e.g., 532 nm from a Nd:Yg laser) and be effectively absorbed by chlorophyll. Simultaneous Raman measurements at 651 nm are also required for baseline calibration. Additional capabilities for detecting fluorescence at high spectral resolution (1-2 nm) would expand the utility of the LIDAR measurements by allowing detection of specific phytoplankton groups through taxon-specific fluorescence features.

Improving Atmospheric Corrections, Ocean Color Algorithms, and Products

The availability of new satellites and additional spectral bands will require improvements in algorithms and atmospheric corrections. In addition, the creation of a more comprehensive field dataset and the use of standardized sampling protocols would significantly increase the quality of data products.

Atmospheric Corrections and Algorithm Development

Advances in bio-optical algorithms and atmospheric corrections are required to make full use of hyperspectral data now becoming available from aircraft sensors. As with atmospheric correction, other types of bio-optical inverse models have been developed by the hyperspectral airborne imaging community. A broad class of such algorithms uses spectrum matching of the atmospherically corrected L_w either to a pre-computed database of spectra or to a semi-analytic model. These spectrum matching approaches use both the radiance magnitude and shape to determine the environmental conditions that generate the best-fit spectrum, i.e., to determine quantities such as bottom depth and type, or water absorption and backscatter coefficients. Spectrum-matching makes full use of the available spectral information at all wavelengths and has proved successful in the inversion of airborne hyperspectral imagery (Mobley et al., 2005; Lesser and Mobley, 2007). These algorithms warrant further investigation by the broad ocean color community. Indeed, it is possible that spectrum matching to the TOA radiances could be used to effect a simultaneous atmospheric correction and bio-optical inversion, but this has been only briefly investigated for multispectral systems (Chomko and Gordon, 2001; Chomko et al., 2003; Stamnes, 2003). Furthermore, the potential for climate change and the complexity of the processes regulating the color of the ocean together raise questions about the suitability of empirical approaches in future oceans. Clearly, empirical band ratio algorithms are locked into the era during which these datasets are collected (Dierssen, 2010). Better assessment of ocean color in the future may come from creating advanced ocean color algorithms that assess independently the different dissolved and suspended materials that absorb and scatter light in the sea.

Similarly, improved atmospheric correction procedures may be required due to global change. Present atmospheric correction approaches assume fixed relationships between near-infrared and visible aerosol optical properties. Changes in the chemistry and light absorption characteristics of aerosols that are expected under future climate conditions would violate the assumption of constancy in aerosol optical properties. Present plans for the ACE ocean ecology spectrometer (OES) include high-quality satellite observations in the ultraviolet spectral region (as short as 345 nm). These planned observations will enable scientists to implement flexible atmospheric correction models that allow aerosol optical properties to vary, as would be anticipated in future climates.

Validation

Even a limited number of comprehensive datasets for selected water and atmospheric conditions would greatly advance ocean color remote sensing and environmental optics in general. A comprehensive dataset would have all the information needed to do a "round trip" radiative transfer (RT) calculation to propagate sunlight from the TOA, through the atmosphere to the sea surface, through the sea surface into the water, from the water back to the atmosphere, and finally through the atmosphere to the sensor (additional details about this round-trip radiative transfer calculation are in Appendix C). This RT process is the physical basis for all ocean color remote sensing and must be fully understood when evaluating the performance of any particular sensor and the products it generates. To date, no entity has collected a truly comprehensive dataset that satisfies these RT needs.

Comprehensive oceanic and atmospheric datasets are needed for:

- development and validation of remote sensing inverse models and algorithms (i.e., TOA ocean color radiances → atmospheric correction algorithm → water-leaving radiance or remote sensing reflectance → bio-optical inversion algorithm → environmental products);
- identification of weaknesses in existing algorithms and guidance for the development of improvements; and
- validation of coupled oceanic and atmospheric RT forward models, which underlie the development of both sensors and algorithms, and of inverse models, which are the foundation of all remote sensing.

Field Data Standards and Standardized Sampling Protocols

The measurements from MOBY, the current U.S. vicarious calibration site off Lanai (Hawaiian Islands), meet strict National Institute of Standards and Technology (NIST) standards. However, users of field instruments that generate data for bio-optical algorithm development or validation do not always meet recommended protocols or use defined calibration standards. Future field observations need standardized, well-calibrated measurements that adhere to protocols to help ensure quantitative comparison of observations.[10] For example, the chlorophyll concentration has long been the principal data product derived from satellite ocean color of interest to oceanographers. There are several different techniques for measuring chlorophyll but no accepted national or international standard protocol. To fill this need, NASA hosted a series of round-robin comparisons to evaluate different methods and to promote guidelines and procedures for measuring chlorophyll.[11] Despite this effort, few research labs to date adhere to these standard procedures developed for chlorophyll. In addition, sky radiance measurements are necessary to characterize, for example, aerosol properties. Similar issues exist for the next-generation products, such as CDOM, particulate organic carbon (POC), particle size distribution, primary productivity, net community production, carbon export flux, etc. Future satellite ocean color missions need to take on the creation and community-wide adaptation of field measurement standards and field sampling protocols for future satellite ocean color data products.

The minimum set of measurements that would need to be made, and for which standards and protocols need to be developed and followed (when appropriate), can be summarized as follows:

Atmospheric measurements:

- Sea level pressure, temperature, humidity, and wind speed
- Cloud condition and sea state
- Sun photometer measurements
- Direct and diffuse spectral irradiance incident onto the sea surface
- Above-surface upwelling spectral radiance in the direction needed to determine the water-leaving radiance

Oceanic measurements:

- Spectral absorption, beam attenuation, and backscatter coefficients
- Measurements of CDOM and CDOM spectral and fluorescence characteristics
- Concentrations of dissolved organic carbon (DOC), POC, and particulate inorganic carbon (PIC)
- Phytoplankton carbon biomass and pigment concentrations
- Net primary production, net community production, and carbon export rates
- Phytoplankton fluorescence and fluorescence quantum yields and taxonomic groups
- Particle size distribution
- Downwelling (and preferably also upwelling) spectral plane irradiance
- Upwelling spectral radiance
- Bottom depth and spectral reflectance in optically shallow waters

Extending Satellite Ocean Color Products to the Vertical Dimension

Ocean color remote sensing provides information only about the surface of the ocean, at spatial scales ranging from kilometers to global. The vertical dimension is only partially explored, from the surface to about 15-20 m in the clearest waters, and from the surface to only a few tens of centimeters in turbid waters (i.e., the "penetration depth" from which originate 90 percent of the photons exiting the water).

However, phytoplankton grow throughout the lit upper layer of the ocean to depths of 100 m or more. Therefore, ocean color sensors miss much of the information of interest; this is particularly true for the Navy, which is interested in optical properties that extend from the surface to the bottom of the ocean.

Determining the total amount of biomass or primary productivity in the ocean currently requires assumptions about how phytoplankton cells are distributed with depth: either homogeneously when the upper ocean is well mixed or with a vertical structure. This vertical structure results from intermingled physical and biological effects and often exhibits a deep maximum whose depth precisely depends

[10] See http://www.ioccg.org/reports/simbios/simbios.html.

[11] See http://oceancolor.gsfc.nasa.gov/DOCS/SH2_TM2005_212785.pdf.

on the balance between physical and biological forcings. The vertical structure is presently reconstructed using statistical relationships between the satellite-derived values and the vertical profile established from in situ information (e.g., Morel and Berthon, 1989; Uitz et al., 2006) or using the concept of biogeographical provinces to which a given shape is assigned (Longhurst, 1998). These techniques use a small number of measured vertical profiles. Consequently, they perform poorly when applied to satellite pixels that include by, definition, all possible cloud-free areas in the ocean.

New autonomous-profiling floats and gliders equipped with optical instrumentation are now available, which provide vertical profiles of quantities such as chlorophyll fluorescence or the particulate backscattering coefficient (Boss et al., 2008; Boss and Behrenfeld, 2010). In the case of gliders, radiance and irradiance sensors are now routinely integrated for subsurface profiles (Schofield et al., 2007). A large deployment of these floats could enhance the satellite data record by providing the missing vertical dimension. Such arrays were initially designed and deployed for physical oceanography (the "Argo" array, e.g., Roemmich and Owens, 2000). These floats sample the water column between the surface and about 2,000 m, covering horizontal scales from ~1 m to ~1,000 km and temporal scales from one day to several years. Interestingly, the intersection between the spatio-temporal domains covered by both remote sensing and profiling floats encompasses the mesoscale oceanic processes as well as the seasonal cycle of mixed layer dynamics and its impact on biomass cycles. These phenomena are fundamental to understanding the impact of physical forcing on ocean biology and biogeochemical cycles.

Such Bio-Argo floats would be an ideal addition to an integrated observing system that includes ocean color satellites, optically equipped gliders, and ship-board studies. These floats would make vertical data available independent of cloud coverage and with good temporal resolution (Claustre et al., 2010). The optical Argo floats could be used to refine the satellite algorithms, improve global primary production estimates, estimate particulate organic carbon in the water, and even estimate the total sinking carbon flux (Bishop and Wood, 2009).

Recommendation: An array of "bio-geochemical floats" should be implemented and progressively expanded.

International collaboration is ongoing in order to build from the experience of the Argo network (e.g., Johnson et al., 2009). The IOCCG has also set up a working group on this topic and will issue a report in 2011.[12]

[12] See http://www.ioccg.org/groups/argo.html.

SUSTAINING OCEAN COLOR REMOTE SENSING OVER THE LONG TERM

Long-Term Mission and Budget Planning

Long-term planning is necessary to provide continuity between satellite missions and to ensure sensor overlap. In general, it takes six to eight years to move an ocean color mission from conception to launch. This time frame can be much longer in a shrinking budget environment or when other problems arise. For example, the SeaWiFS concept was developed in 1986, but launch did not occur until 1997. Furthermore, mission and budget plans need to include provisions for all mission requirements throughout the mission's life span and beyond. SeaWiFS was successful in part because mission planning and budget, through support from the EOS/MODIS program, included provisions not only for the sensor and satellite, but also for many of the essential elements such as vicarious calibration, stability monitoring, collection of in situ validation data, and a mission team with the tools to handle data processing and reprocessing. In addition, SeaWiFS experienced a long launch delay, which provided sufficient time to make sure the necessary infrastructure was in place for the calibration and validation effort. Less than a year from the launch date, it remains unclear who will fund and conduct the vicarious calibration for VIIRS on NPP and who will be processing and reprocessing the data. In addition, planning for in situ data collection has begun only recently. These missing elements of the VIIRS/NPP mission contribute significantly to the uncertainty about the data quality of its ocean color radiance and ocean color products, and if unresolved, might jeopardize the success of the mission.

Conclusion: A satellite mission that does not include planning and budgeting for all essential elements of a mission (e.g., vicarious calibration, stability monitoring, in situ data collection and archiving, algorithm development, data processing and reprocessing; see Chapter 3 for additional details), jeopardizes the success of the mission for many uses, especially for climate assessments.

Recommendation: To ensure success, a mission should include long-term planning and budgeting for all requirements of the mission.

Long-Term Planning for Data Stewardship

As discussed in previous chapters, producing high-quality ocean color data is complex and requires a concerted effort. As information becomes available about the sensor's behavior, the continuous vicarious calibration effort and data reprocessing at regular intervals are vital to generate high-quality products. Therefore, plans for product development and data access and archiving need to be in place well in advance of the sensor launch. Plans also need to specify how efforts carry over from one mission to the next to preserve data continuity.

Currently, NASA's Ocean Color Biology Processing Group (OBPG) at Goddard Space Flight Center (GSFC) is internationally recognized as a leader in producing well-calibrated, high-quality ocean color data products from multiple satellite sensors. For example, processing and reprocessing from Level 0 to Level 2 imagery require the most skill and resources, including access to pre- and post-launch calibration data, models, ancillary data and significant computational resources for production, archiving, and distribution. In effect, these production steps determine the quality of the final data products. Access to all raw, processed, and metadata are critical if long-term time-series of ocean color products are to be constructed across different mission datasets (à la Antoine et al., 2005).

The Ocean Color Biology Processing Group at NASA GSFC currently provides this service for CZCS, SeaWiFS, and MODIS data. As new algorithms are developed, the OBPG has repeatedly reprocessed all ocean color data from SeaWiFS and MODIS to ensure a continuous, intercalibrated dataset of climate-quality data. To be able to routinely reprocess the data, the raw data, radiance at the TOA, and water-leaving radiance needs to be archived and available for the long term. In particular, the most recent version of the water-leaving radiance needs to be readily available to ensure users can generate their own derivative products.

The OBPG currently provides broad access to ocean color data by creating and deploying SeaWiFS Data Analysis System (SEADAS), an image-processing software that can be installed on many different computer platforms. The OBPG has developed the necessary modules to make data easily accessible and has built the necessary structure to archive the data, including the radiance at TOA and the water-leaving radiance. NOAA is currently building capacity but does not have the know-how to provide these comprehensive services. Although NOAA's National Climate Data Center (NCDC) plans to archive a climate-level[13] radiance data record, it is unclear how accessible the data will be. Easy access will be an important factor in contributing to the successful application of the ocean color data.

Conclusion: Because of the potential need to reprocess the raw data years after collection, the committee concludes that the water-leaving radiance and the radiance at the TOA need to be archived together with the metadata for the long term. In addition, the most recent version of the water-leaving radiance needs to be readily accessible to all users.

Conclusion: A permanent archive for repackaged Level 0 data and metadata is required to allow subsequent reprocessing and merging of individual mission data into sustained climate data records.

Both NASA and NOAA support ocean color applications, with NASA focused primarily on research and development and NOAA focused on operational uses. Because both agencies have a strong interest in climate and climate impacts, they share a common interest in climate data records (CDRs).

As previously discussed, NOAA currently lacks the demonstrated capacity to readily produce high-quality ocean color products. Moreover, the committee anticipates major challenges to generating high-quality products from the VIIRS/NPP data. However, a recent NOAA report (NOAA, 2010) makes a recommendation to build the in-house capacity for end-to-end data processing/reprocessing. If NOAA builds its own data processing/reprocessing group, two independent federal groups will be developing ocean color products. Having two groups independently process ocean color data would provide the benefit of products that could be tailored to the respective user-group. However, it results in some redundancy and potential questions about merging datasets for building long-term climate records. Given NASA's experience with end-to-end data processing, NOAA can draw on that agency's expertise to build its own capacity.

Conclusion: NOAA would greatly benefit from initiating and pursuing discussions with NASA for an ocean color mitigation partnership that would build on lessons learned from SeaWiFS and MODIS, in particular.

A near-term option for the partnership could be a real or virtual "center" involving NOAA and NASA personnel, with contributions from the academic research community. An important step in any research-to-operations transition is for researchers to work directly with the people developing operational capabilities. Thus, such a virtual center's activities could include: research and development related to ocean color products that serve research and operational users; and processing/reprocessing of data from U.S. and foreign ocean color missions to ensure a sustained time-series of calibrated imagery to identify long-term trends and calibration and validation activities. These involve for example, a NOAA-operated MOBY-like site, among other activities.

Recommendation: To move toward a partnership, NASA and NOAA should form a working group[14] to determine the most effective way to satisfy each agency's need for ocean color products from VIIRS and to consider how to produce, archive, and distribute products of shared interest,

[13] Climate-level means repackaged data so they look like a MODIS granule and metadata repackaged accordingly to ease the reprocessing of the Level 0 data.

[14] The committee was informed in March 2011 that NOAA and NASA have formed a new ocean color working group with a composition and charge that encompasses many of the recommendations listed above.

such as CDRs, that are based on data from all U.S. ocean color missions. This group should be composed of agency representatives and also include outside experts from the ocean color research and applications community.

This working group could be the focal point for U.S. contributions to the Ocean Colour Radiometry Virtual Constellation (OCR-VC), for articulating U.S. needs for specific data from international missions, and for helping negotiate how those needs would be met. As is currently done by the Ocean Color Group at GSFC, the new working group would be the ideal mechanism to routinely interact with ocean color experts in the national and international academic community. Subcommittees of existing federal advisory committees—the Earth Science Subcommittee of the NASA Advisory Committee and NOAA's Scientific Advisory Board (SAB)—could provide oversight. To the extent possible, the working group could develop and maintain centralized teams with all necessary skills to evaluate product quality and to take appropriate measures to improve quality for the long term. These teams would provide avenues for stakeholders to engage and would enable the research community to continuously demonstrate its need for, and ensure the existence of, overlapping programs that can maintain the essential requirements (i.e., missions and accompanying infrastructure) to generate multi-decadal climate-quality data records. To achieve a multi-decadal climate-quality data record will necessitate a permanent planning function at the international level (see discussion below).

Recommendation: This working group should engage with the scientific community, develop a unified and coordinated voice, provide long-term vision and oversight, and engage with the international community.

Building and Maintaining the Ocean Color Workforce

Developing and using high-quality ocean color research products requires a highly specialized and trained workforce with a diverse set of technical skills. Maintaining the viability of the field requires experts who know how to design and build a sensor; test and calibrate it; design and operate vicarious calibration sites; conduct validation and calibration efforts; process, reprocess, and archive ocean color data; and make these products easily available to users. In addition, data users need to be trained in satellite oceanography.

Building and Maintaining the Expertise in Government Agencies

As we learned from the SeaWiFS/MODIS experience, a team with the right mix of skills and knowledge is essential to advancing the quality of ocean color products. A group of experts needs to take responsibility for acquisition, processing, reprocessing, calibration, validation, model implementation, and distribution for satellite ocean color data. Ideally, such a group will be flexible and able to respond to and resolve a wide range of issues; the OBPG at GSFC responsible for SeaWiFS and MODIS ocean color data products provides a good model. The team has all required scientific, engineering, and technical skills to interact, for example, with competitively selected NASA science teams for individual missions.

The committee judges it to be most efficient to establish an interagency team to be involved with all ocean color missions over the long term and to interact with competitively selected science teams for individual missions. This would minimize the loss of institutional memory.

Conclusion: Long-term planning is needed that focuses on building a long-term data record, instead of focusing on building individual satellite missions. A working group that is maintained across missions is the best choice to coordinate this planning.

Specialized technical and scientific expertise in various aspects of ocean color radiometry exists within the civil service at NASA, NOAA, NIST, Office of Naval Research (ONR), and the Naval Research Laboratory (NRL), and is concentrated at NASA's GSFC. This expertise includes sensor design and calibration, aerospace engineering, systems engineering, hydrological optics, physics, atmospheric physics, biogeochemistry, etc. Maintaining strong technical expertise within the civil service allows the agencies to tackle technical questions quickly, to provide technical oversight of major instrument contracts, and to support the vigorous exchange of scientific ideas with the academic community and other agencies.

Recommendation: NASA and NOAA should ensure sufficient levels of staffing in areas critical to the continuation of ocean color research and climate data collection.

The committee also encourages NASA and NOAA to expand the use of academic researchers in Intergovernmental Personnel Act[15] positions both in managerial and technical roles. This will expand the influx of ideas from academia into the federal agencies and will increase the number of academic researchers familiar with government procedures and policies. Similarly, NASA and NOAA could enter into agreements to facilitate temporary exchange of scientists and engineers to encourage sharing of ideas and understanding of each agency's missions, strengths, and weaknesses.

[15] Through the IPA program, NASA or NOAA can temporarily bring individuals from academia and state and local governments to the agency to provide scientific, administrative, and managerial expertise.

Building and Maintaining the Expertise in Academia

Experience from all NASA ocean satellite missions demonstrates the importance of supporting a competitive research program associated with each mission. Researchers help improve data products, advance ocean color applications, and train the new workforce.

Scientists have contributed to significant, and in some cases, immediate improvements to data products by conducting research on topics such as in-water and atmospheric algorithms, sensor performance, and regional validation of in-water and atmospheric correction algorithms. This research can provide critical feedback to the mission if there is clear communication with the project team, via open meetings and workshops where results are discussed and their meaning debated.

For example, application scientists were among the first to note that initial SeaWiFS processing had yielded anomalous water-leaving radiance spectra with unusually low radiance in the blue bands (in fact, negative radiances in many coastal waters). It required several years of interaction between applications scientists and the SeaWiFS project, and several reprocessings, to fix the problem.

In addition, NASA, NSF, and NOAA have supported investigators who use ocean color imagery for basic research. The applications described in Chapter 2 lead to better understanding of ocean processes and make important societal contributions.

Further, competitive research programs often result in new applications for or new approaches to using ocean color data; these new applications add value to the mission. Lastly, research projects naturally integrate graduate students into the ocean color community, which is critical to maintain a capable workforce in the private sector, at NASA and at NOAA, with continuity through missions.

Training and Recruitment Through Summer Courses

Many scientists in academia and government, and several federal agency program managers, are graduates of summer courses such as those at the University of Maine or Cornell University. For example, the intensive summer course in optical oceanography and remote sensing at the University of Maine was first taught in the mid-1980s by experts from around the world. It is held every two or three years and has achieved an international reputation as a career-molding course. Applications always far outnumber the 12 to 15 seats available. The course has evolved with the science to include lectures and extensive hands-on laboratory and field work, using many instruments of optical oceanography and vicarious calibration. NASA and other federal agencies have provided substantial funding for the course.

The IOCCG is currently organizing a recurring summer lecture series, "Frontiers in Ocean Optics and Ocean Colour Science." This class would build on and complement other courses. While the course at the University of Maine focuses on hands-on training with a strong laboratory and field component, the IOCCG course would focus on current critical issues and emerging topics of optical oceanography and ocean color remote sensing research.

The large number of applications for ocean color products demonstrates the demand for these intensive summer courses. The limitation in both cases is funding to cover faculty salaries, travel, laboratory and field costs, and student per diem expenses. The committee considers such costs to be small compared to the benefits of maintaining a highly trained and skilled workforce.

Collaborating and Coordinating Internationally to Sustain Ocean Color Observations

Two international committees—the IOCCG and the OCR-VC[16] organized under the Committee on Earth Observing Satellites (CEOS)—support international cooperation for ocean color research and operations. The IOCCG is a committee of users and space agency representatives. Among the primary IOCCG products are monographs on a wide range of topics that provide essential consensus advice to those planning and operating satellite ocean color missions. The OCR-VC is a consortium of representatives from agencies that operate satellite ocean color missions. It seeks to coordinate activities related to post-launch calibration and validation, data merging, and sharing of essential pre-launch characterization and calibration information. OCR-VC also promotes training programs and outreach.

The activities of the IOCCG and OCR-VC are increasingly important to U.S. users of satellite ocean color products because neither NASA nor NOAA will provide all required data products for at least a decade. For example, the United States currently has no geostationary mission in orbit and limited availability of high spatial resolution imagery (250- to 300-m pixels). Second, non-U.S. missions have the potential to provide essential backup for global imagery in the event of a failure during the launch or in the early stages of a U.S. mission. Finally, merging data from multiple sensors significantly enhances global coverage. For these reasons, it is essential that NASA and NOAA continue to support the activities of the IOCCG and the OCR-VC.

The production of a climate-quality long-term record of ocean color requires international collaboration. As discussed above, establishing a climate-quality long-term data record exceeds the capacity and mandate of a single U.S. agency. In general, it is difficult to maintain such long-term commitments due to budget uncertainties. International collaboration to establish a long-term record can be a good hedge against the uncertain funding from any single space agency or nation.

[16] See http://www.ioccg.org/ groups/OCR-VC.htm.

Examples of successful international collaboration already exist in several domains. The Centre National d'Etudes Spatiales (CNES) and NASA have established a fruitful partnership to prepare, implement, and exploit altimeter missions (Jason series and Topex/Poseidon), leading to long-term, global sea-level data records that demonstrate a gradual increase in sea level (IPCC, 2007). The Group for High-Resolution Sea Surface Temperature (GHRSST) has brought together many space agencies involved in measuring sea surface temperature from space in order to establish standards, perform comparisons of products and algorithms, and produce global datasets by merging data from different satellites.

These efforts involved not only space agencies but also the science community, which has to be organized in order to have a strong and single voice. The ocean color community still lacks this mechanism, but the creation of the OCR-VC represents a step forward. The OCR-VC provides a framework for agencies to strengthen collaboration and leverage individual efforts. The IOCCG is considering options for how to make such a virtual constellation a reality for the ocean color community.

Another promising development is ESA's Climate Change Initiative (CCI) to produce Essential Climate Variables (ECV; CDRs in NOAA/NASA terminology). ESA selected ocean color as one of the first 10 ECV projects that began in summer 2010. The goals for the ocean color ECV are: generate the most complete multi-sensor global satellite data products for climate research and modeling that meet Global Climate Observing System (GCOS) ocean color ECV requirements; quantify pixel uncertainties for different regions; and assess the applicability and impact of ocean color ECV products on ecosystem and climate models. Another key goal is to form teams of observational scientists and climate modelers to ensure that ECVs are correctly incorporated in climate models and models of climate impacts.

ESA recognizes the importance of international cooperation for this project and lists NASA, NOAA, JAXA, and the IOCCG as external partners. Further, a closer NASA/NOAA-led partnership with ESA would be a major contribution to the OCR-VC and could stimulate participation by other agencies (e.g., JAXA, ISRO), potentially bringing other expertise and satellite datasets into the project. From users' perspective, this international partnership could go a long way toward providing high-quality ocean color data from many different missions and for many applications.

Prototype products of the first 10 ECVs will be available in 2011-2012. Complete time-series (from multiple sensors) will be available beginning in mid-2013. The objective for the ocean color time-series is to reduce bias among sensors (MERIS, SeaWiFS, and MODIS) to less than 1 percent, an ambitious goal that will require reprocessing of all satellite datasets.

A NASA/NOAA-led project, similar to NASA's SIMBIOS program, could help meet this goal and complement the ESA effort. Essential components would include revisiting calibration factors and how they change over time for multiple sensors; updating in situ databases for product validation; evaluating quality of in situ data; generating match-up datasets (satellite and in situ) to confirm accuracy; incorporating VIIRS/NPP data into the time-series; and other activities.

Conclusion: The CCI initiative presents an opportunity for real progress toward establishing a seamless time-series for a climate-quality ocean color data record. Engaging experts at NASA and NOAA could significantly contribute to the success of this initiative with mutual benefits for the United States and the international community.

Conclusion: The IOCCG is the logical entity to lead the planning and to build international support for the establishment of a global climate-quality ocean color data record. NASA's and NOAA's support for and engagement with this group will be essential to the success of these efforts.

CONCLUSION

The expanding user community and the diversity of ocean color applications that fuel research and benefit ocean ecosystem health demonstrate the critical need to sustain and advance ocean color observations from satellites well into the future. As discussed in detail in Chapter 2, ocean color remote sensing is the only way to obtain a global view of the ocean biology. Ocean color data are essential to improving the understanding of the climate system, including global carbon fluxes. Ocean color satellite observations also are used to assess the health of the marine ecosystem and its ability to sustain important fisheries. Any interruption in the ocean color record would severely hamper the work of climate scientists, fisheries and marine resource managers, and an expanding array of other users, from the military to oil spill responders.

Increasing the spatial or temporal resolution, especially in coastal waters, would enable further advances in research and resource management. In particular, an ocean color satellite in geostationary orbit would fill an important gap in observational capability (Appendix D). High spectral imaging and a satellite in geostationary orbit would significantly improve the ability to monitor for example HABs and coral reef health. Similarly, the addition of Bio-Argo floats would turn the two-dimensional satellite ocean color imagery into dynamic three-dimensional depictions of the ocean biosphere. These and other enhancements described above would add tremendous value to oceanography, but they will be difficult to balance with the requirements to simply maintain the current capabilities, especially in the current budget environment. Thus, it will require careful and strategic long-term planning, in addition to international collaboration and coordination, to meet these diverse needs.

Mission planning proved the concept (CZCS) and led to the successful demonstration that water-leaving radiance can be of such high accuracy that climate trends can be quantified (SeaWiFS and MODIS). However, building a climate-quality time-series comes with stringent requirements—most notably the need for continuity and sensor inter-calibration. Now, planning will need to extend beyond the next mission and establish a strategy to sustain the climate-quality data record.

Conclusion: A data-oriented long-term planning approach will need to replace a mission-oriented approach for the global climate-quality ocean color record.

To develop this climate-quality time-series and to advance ocean remote sensing, strategic long-term planning and budgeting is required for all aspects of follow-on missions, including how data are reprocessed, accessed, and stored across the individual missions. In addition, the institutional memory and workforce need to be maintained and transitioned across individual missions to ensure some measure of consistency and to avoid inefficiencies. NOAA and NASA will continue to have mutual interests in the ocean color climate data record as well as in advances in remote sensing. Therefore, they would benefit from sharing in the development of these long-term plans.

Going forward, a national working group similar to the international IOCCG working group, with strong governance, clear mandate, and financial resources, is needed to guide the direction of ocean color remote sensing in the United States and to implement changes at the national level. This committee also would provide oversight and long-term vision for the development of U.S. ocean color missions and the delivery of ocean color products to users. The long-term vision also needs to ensure the next generation of satellite oceanographers is sufficiently trained in order to maintain the required expertise at every level, from sensor engineering to data processing and application.

In the long term, simply sustaining the current capabilities of ocean color remote sensing will fall short of supporting the array of ocean color applications described in Chapter 2. Many ocean color applications require a commitment to advancing current capabilities. Foremost, these advances need to include hyperspectral and active imaging capabilities and a sensor in geostationary orbit for coastal applications.

Therefore, the committee recommends above that NASA and NOAA form a working group to determine the most effective way to satisfy each agency's need for ocean color products from VIIRS and future ocean color sensors. This working group could be the focal point for U.S. collaborations with the international community and for articulating U.S. needs for specific data from international missions, for helping to negotiate how those needs will be met and for advocating for advanced capabilities to support future ocean color applications.

Moreover, because the community will require distinct types of satellite sensors to meet all data product needs, no single nation will be able to develop or even maintain capabilities on its own. NASA and NOAA will need to continue to actively engage and contribute to the development of the international OCR-VC. Ocean color remote sensing needs to be an internationally shared effort.

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Appendix A

Past, Present, and Planned Sensors

Past Sensors

Coastal Zone Color Scanner (CZCS)

Sensor/Satellite	Agency	Mission Duration	Swath	Resolution	Bands	Spectral Coverage (nm)
CZCS	NASA (USA)	1978-1986	1,556 km	825 m	6	433-12,500

Sensor Description:

The CZCS was the first satellite sensor devoted to ocean color imaging. Out of six spectral bands, four were used primarily for ocean color. These four bands were centered at 443, 520, 550, and 670 nm with a 20-nm bandwidth. The mission goal was to test whether satellite remote sensing could be used to identify and quantify suspended and dissolved material in the surface ocean. The sensor successfully demonstrated that ocean color could be used to quantify chlorophyll and sediment concentrations in the ocean. It provided the justification for SeaWiFS and MODIS.

Calibration:

The instrument was calibrated pre-launch. The on-orbit calibration was to have been accomplished by a built-in incandescent light source. The light source was redundant in case of failure and was calibrated using the instrument itself. The light from the lamp was used only to verify instrument stability with time. The calibration revealed the degradation of the sensitivity in the visible bands (Evans and Gordon, 1994). The vicarious calibration was conducted using post-launch validation cruises and the chlorophyll time-series from Bermuda.

Data Availability:

CZCS data are freely accessible.

Applications:

CZCS data were used to demonstrate the feasibility of ocean color remote sensing and its application to measuring global phytoplankton biomass and productivity. Because of the limited power, it could operate only a few hours per day.

Sea-Viewing Wide Field-of-View Sensor (SeaWiFS)

Sensor/Satellite	Agency	Mission Duration	Swath	Resolution	Bands	Spectral Coverage (nm)
SeaWiFS	NASA (USA)	1997-2010	2,806 km	1,100 m	8	402-885

Sensor Description:

The SeaWiFS mission was launched by the Orbital Sciences Corporation in 1997. It was a medium-spectral resolution imaging spectroradiometer operating in the visible to near-infrared spectral range, aboard the polar sun-synchronous OrbView-2 (OV-2) satellite. The sensor collected data in eight spectral bands (see Chapter 4; Table 4.5) from 402 to 885 nm. The instrument tilted ±20 degrees to minimize sun glint.

Calibration:

SeaWiFS mission used MOBY water-leaving radiances for the vicarious calibration and near-monthly lunar looks to track spectral band degradation over time. The mission included an extensive calibration/validation program using global in situ measurements for product validation.

Data Availability:

Data can be freely and openly accessed.[1] Global data are freely distributed at Level 1 (TOA total radiances in eight bands), Level 2 (geophysical products such as the spectral marine reflectances and the chlorophyll concentration), and Level 3 (global gridded products).

Applications:

The NASA Ocean Color Group distributes the following products, which are used for a large array of applications described in Chapter 2:

Radiances at 412, 443, 490, 555, 670 nm; aerosol optical thickness at 865 nm; epsilon of aerosol correction at 765 and 865 nm; OC4 Chlorophyll a concentration; diffuse attenuation coefficient at 490 nm; Angstrom coefficient, 510-865 nm; Photosynthetically Active Radiation from the sun 400-700 nm; Normalized Difference Vegetation Index; Land Reflectance and a SeaWiFS Biosphere product.

[1] See http://oceancolor.gsfc.nasa.gov/.

GLI

Sensor/Satellite	Agency	Launch Date	Swath (km)	Resolution (m)	Bands	Spectral Coverage (nm)
GLI/ADEOS II	NASDA (Japan)	2002-2003	1,600	250/1,000	36	375-12,500

Sensor Description:

The Global Imager (GLI) was launched in 2002 aboard ADEOS II, which also carried POLDER-2 [Polarization and Directionality of the Earth's Reflectances]. GLI is designed to provide frequent global observations of reflected radiance of the ocean, clouds, and land. The sensor has a multi-spectral observation capability with 36 bands and ground resolution of 1 km. Some channels have a resolution of 250 m.

Calibration:

Vicarious calibration was performed. Results of vicarious calibration workshop are available online.[2]

Data Availability:

Data products are available online.[3]

Applications:

Ocean color, water-leaving radiances and aerosols.

[2] See http://suzaku.eorc.jaxa.jp/GLI/cal/index.html; accessed October 25, 2010.
[3] See http://www.eorc.jaxa.jp.

Current Sensors in Polar Orbit

Moderate Resolution Imaging Spectroradiometer (MODIS) on TERRA and AQUA

Sensor/Satellite	Agency	Launch Date	Swath	Resolution	Ocean Color Bands	Spectral Coverage (nm)
MODIS (Terra)	NASA (USA)	1999	2,330	250/500/1,000	9	405-14,385
MODIS (Aqua)	NASA (USA)	2002	2,330	250/500/1,000	9	405-14,385

Sensor Description:

MODIS is a key instrument aboard the Terra (EOS AM) and Aqua (EOS PM) satellites designed for land, atmosphere, and ocean observations. Terra's orbit around Earth is timed so that it passes from north to south across the equator in the morning, while Aqua passes south to north over the equator in the afternoon. MODIS-Terra and MODIS-Aqua are viewing the entire Earth's surface every one to two days, acquiring data in 36 spectral bands, or groups of wavelengths.

Calibration:

MODIS is calibrated using a combination of solar and lunar viewing to track spectral calibration and temporal degradation as well as vicarious calibration using in situ observations of water-leaving radiance.

More recently, SeaWiFS imagery also had to be used to address sensor degradation issues.[4]

Data Availability:

All data and products (Levels 0-4) are freely available online[5] via network download. Products: Normalized water-leaving radiance at 412, 443, 488, 531, 551, and 667 nm; aerosol optical thickness at 869 nm; epsilon of aerosol correction at 748 and 869 nm; diffuse attenuation coefficient at 490 nm; Angstrom coefficient, 531-869 nm; and sea surface temperature.

Applications:

MODIS serves a large array of applications including process and climate research and many resource managment applications.

[4] See http://www.opticsinfobase.org/abstract.cfm?uri=ao-44-26-5524.
[5] See http://oceancolor.gsfc.nasa.gov/.

MERIS Instrument, on Board the ENVISAT Platform

Sensor/Satellite	Agency	Launch Date	Swath	Resolution	Bands	Spectral Coverage (nm)
MERIS	ESA (Europe)	2002	1,150	300/1,200	15	412-900

Sensor Description:

MERIS is an ESA-led mission (Rast and Bézy, 1995; Rast et al., 1999). It is a medium resolution imaging spectroradiometer operating in the visible to near-infrared spectral range, aboard the sun-synchronous ENVISAT platform. It is set up with 15 spectral bands from 412 to 900 nm. MERIS is a "push-broom" spectrometer, with linear CCD arrays providing spatial sampling in the across-track direction, while the satellite's motion provides scanning in the along-track direction. The MERIS field of view is 68°5 around nadir, which gives a swath width of 1,150 km covered by five identical optical modules (cameras) arranged in a fan shape configuration. The spatial resolution at nadir is 300 m (full resolution products), and is degraded to 1.2 km by a 4 × 4 pixel averaging (reduced-resolution products). Global coverage is obtained in three days (irrespective of clouds and sun glint).

Stability Monitoring:

Radiometric calibration uses two onboard solar diffusers. Spectralon is a very good reflectant with very well-characterized reflectance characteristics. Spectralon is subject to reflectance change over time after cumulative exposure to solar radiance, in particular to ultraviolet exposure. Because frequent solar views are required to monitor the sensor stability, the degradation of the Spectralon also must be monitored. Therefore, the first diffuser is used every two weeks for routine calibration, and the second one is used every three months and therefore tracks possible degradation of the first one. An erbium-doped diffuser is used for spectral calibration. MERIS was launched in May 2002 for an initial and nominal five-year mission, which has been extended so that operations should continue through 2013.

Data Availability:

Open access. Global data are freely distributed at Level 1 (TOA total radiances in 15 bands), Level 2 (geophysical products such as the spectral marine reflectances and the chlorophyll concentration), and Level 3 (global gridded products).

Applications:

MERIS radiometric capabilities were set up in the 1990s to meet predefined requirements for ocean color remote sensing (e.g., Gordon, 1987, 1988, 1990, 1997; Antoine and Morel, 1999). The onboard devices have proven very efficient in maintaining a high radiometric accuracy and stability.

With respect to coastal applications, the current MERIS instrument has considerable advantages over SeaWiFS, MODIS, and VIIRS, given its comparatively high spatial resolution and many more spectral bands. No U.S. instrument will have MERIS capabilities for the foreseeable future.

The higher spatial resolution of MERIS resolves coastal features such as plumes and fronts that are not evident in the coarser resolution of the NASA sensors. The higher spectral resolution of MERIS enables more sophisticated algorithms for complex coastal waters. The Naval Research Laboratory at Stennis Space Center is currently using full resolution MERIS imagery to support assimilation of satellite-derived optics into ocean models that provide forecasts on time scales of 24-48 hours. NOAA is now acquiring MERIS high spatial resolution imagery in near-real time (ca. 12 hours) for U.S. coastal waters. NOAA's Center for Coastal Monitoring and Assessment (CCMA) is using MERIS imagery to assess and forecast coastal and marine ecosystem conditions, including for harmful algal bloom (HAB) forecasts. During summer 2010, CCMA had operational programs to detect cyanobacteria and other HAB organisms in Lake Erie, Chesapeake Bay, and Florida coastal waters. According to NOAA's Dr. Richard Stumpf, the MERIS "red bands" (centered at 620, 665, 680, and 709 nm) are particularly useful for CCMA HAB forecasts. There also is high potential for using these red bands as an alternative approach for retrieving chlorophyll in coastal waters. Algorithms based on these four bands are substantially unaffected by atmospheric correction errors. This is particularly important given the complexity of the atmospheres over the coastal ocean and inland waters.

COCTS-CZI

Sensor/Satellite	Agency	Launch Date	Swath	Resolution	Bands	Spectral Coverage (nm)
COCTS-CZI/HY-1B	CNSA (China)	2007	1,400/500	250/1100	10/4	402-12,500/433-885

With the exception of the general specifications in the table above, the committee did not obtain additional information on the status or performance of the Chinese Ocean Colour and Temperature Scanner/Coastal Zone Imager (COCTS-CZI).

OCM-2

Sensor/Satellite	Agency	Launch Date	Swath	Resolution	Bands	Spectral Coverage (nm)
OCM-2/Oceansat-2	ISRO (India)	2009	1,420	360/4,000	9	400-900

Sensor Description:

OCM-2 was successfully launched in 2009 on board ISRO's OCEANSAT-2 spacecraft. OCM-2 has the same design and specifications as OCM with the exception of a shift in spectral bands 6 and 7 (Chauhan and Navalgund, 2009). The original 670 nm band (band 6) has shifted to 620 nm; the 765 nm band (band 7) has shifted to 740 nm to avoid oxygen absorption. These improvements are expected to provide greater accuracy of the normalized water-leaving radiance in the shorter wavelengths due to improved atmospheric corrections. The instrument was designed to provide continuity with the OCM instrument.

The OCM-2 sensor has a swath of 1,420 km and similar bands to OCM, with two changes: The 765 nm channel has been moved to 740 nm to avoid O_2 absorption, and the 670 nm channel has been replaced by a 620-nm channel for better quantification of suspended sediments. Oceansat-2 has two modes of operation: Local Area Coverage (LAC) with 360-

m real time transmission, and Global Area Coverage (GAC) with 4-km onboard recording and playback. GAC data coverage is between ± 75° latitude covering the full globe in eight days. The OCM-2 instrument is currently providing excellent datasets. The instrument has a tilting mechanism and the tilt is changed twice per year depending on seasonality, providing minimum sun glint over Indian waters.

Calibration:

OCM-2 includes a solar and lunar calibration (lunar look once every six months) to assess sensor degradation.[6] A permanent cal/val site has been set up in the Lakashadweep Sea, and data from an optical buoy are being used for vicarious calibration of OCM-2 data. Extensive ship campaigns will also be organized for validation of geophysical data products. The NRSA Data Center (NDC) will carry out dissemination of 4-km GAC data products on the Internet after the cal/val phase of the mission. A Letter of Intent with NASA/NOAA for OCEANSAT-2 data sharing was signed last year.

Data Availability:

Open access[7] users will be provided with Level 1-B basic radiance products (atmospherically corrected), which can be displayed using SeaDAS. Level 2 products will consist of chlorophyll-a concentration, Total Suspended Matter (TSM), diffuse attenuation coefficients (K_d-490 nm), and Aerosol Optical Depth (AOD) at 865 nm and Level 3 (weekly and monthly averages generated on trial basis). Level 1 and 2 data are available at a nominal cost directly from the National Remote Sensing Centre (NRSC).

Level 3 products will consist of weekly, monthly, and yearly binned products (4 km). An OC-4-type algorithm has been developed for OCM-2 using bio-optical archived data collected in the Arabian Sea as well as data from NOMAD.

[6] See http://www.ioccg.org/sensors/Navalgund_OCM-2.pdf; accessed October 22, 2010.

[7] http://www.ioccg.org/sensors/Navalgund_OCM-2.pdf; accessed October 22, 2010.

Current Sensors in Geostationary Orbit

Korean COMS-1 GOCI

Sensor/Satellite	Agency	Launch Date	Swath	Resolution	Bands	Spectral Coverage (nm)
GOCI/COMS	KARI/KORDI (S. Korea)	2010	2,500	500	8	400-865

The Korea Aerospace Research Institute (KARI) developed and launched a GEO ocean color imager (GOCI) on June 26, 2010, that is spectrally similar to the Sea-viewing Wide Field-of-view Sensor (SeaWiFS). GOCI offers 360-m nadir ground sample distance (GSD; close to the CWI 300 m requirement) with sensor-provided pointing knowledge of 10 mrad, corresponding to 360-m nadir pointing uncertainty (Faure et al., 2007). While the system (Figure A.1) is located for Asian seaboard imaging and therefore does not provide western Contiguous United States (CONUS) coastal imagery, it should allow sub-diurnal GEO coastal marine data-efficacy verification.

KARI's Communication and Ocean Monitoring Satellite (COMS) on which GOCI is mounted provides telecommunications as well as GOCI data from a relatively small (2,300 kg) GEO spacecraft. This is less than the mass of larger (3,200 kg) commercial GEO communications satellites, yet carries the GOCI instrument that has 78-kg mass, 100-W power, 1.4 × 0.8 × 0.8 m dimensions (x, y, z; z = nadir), with data rate dependent on custom-selected GOCI integration time per spectral band (Faure et al., 2007).

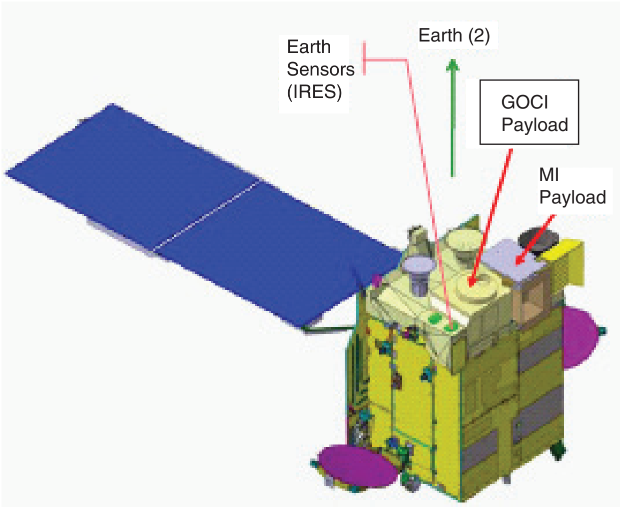

FIGURE A.1 South Korean COMS-1 satellite with geostationary ocean color imager (GOCI) and the Asian seaboard viewing area. SOURCE: Faure et al., 2007; used with permission from Astrium.

TABLE A.1 GOCI Spectral Capability.

Central Wavelength (nm)	SeaWIFS (bandwidth, nm)	GOCT (bandwidth, nm)	Primary Use
412	1(20)	1(20)	Yellow substance and turbidity
443	2(20)	2(20)	Chlorophyll absorption maximum
490	3(20)	3(20)	Chlorophyll and other pigments absorption, K(490)
510	4(20)		Chlorophyll absorption
555	5(20)	4(20)	Suspended sediment
660		5(20)	Fluorescence base 1, chlorophyll, suspended sediment
670	6(20)		Atmospheric correction
680		6(10)	Fluorescence signal, atmospheric correction
745		7(20)	Atmospheric correction, fluorescence base 2
765	7(40)		Atmospheric correction, aerosol radiance
865	8(40)	8(40)	Aerosol optical thickness, vegetation, water vapor reference over the ocean

The GOCI spectral capability (Table A.1) is modest, with a filter wheel to select one of eight SeaWiFS-like spectral bands at a time. Nevertheless, the GOCI provides a case study of the benefits of GEO vs. LEO ocean color sensing via comparison of GOCI MODIS/SeaWiFS ocean color data. The committee believes it likely that NASA will conclude that even GOCI-like data, if located over CONUS, would provide coastal data to partially close the existing ocean color data gap. Therefore, were there a low-cost means (compared to the estimated cost of a GOES-R satellite, for example) to place such a system in GEO, perhaps NOAA and NASA would consider it.

Future Sensors in Polar Orbit

VIIRS on NPP and JPSS 1 & 2

Sensor/Satellite	Agency	Launch Date	Swath	Resolution	Bands	Spectral Coverage (nm)
VIIRS/NPP	NOAA (USA)	2011	3,000	370/740	22	402-11,800
VIIRS/JPSS 1&2	NOAA (USA)	After 2015	3,000	370/740	22	402-11,800

Sensor Description:

The Visible Infrared Imager Radiometer Suite (VIIRS) is a multi-spectral scanning radiometer scheduled to launch in 2011. VIIRS was designed to provide global observations of land, ocean, and atmosphere parameters at high temporal resolution (~ daily). It consists of a multi-spectral scanning radiometer (with 22 bands between 400 and 1,200 nm) with a swath width of 3,000 km.

Calibration:

A single solar diffuser and four lunar calibration looks per year if no orbital maneuvers are permitted.

Initial calibration will utilize matches with MODIS-Aqua. If resources can be mobilized to fund MOBY, MOBY water-leaving radiances will be incorporated as part of the vicarious calibration. The calibration for VIIRS on JPSS is likely to model the calibration of VIIRS on NPP, although the details regarding lunar maneuvers and a MOBY-like approach to vicarious calibration has to be determined.

Data Availability:

NOAA CLASS facility; open availability.

Applications:

Water-leaving radiance and chlorophyll.

OLCI Instrument on the Sentinel-3 platform

ESA is currently developing three satellite systems that form part of the Space Component of the European GMES (Global Monitoring for Environment and Security) program. The Sentinel-3, one of these missions, carries the wide-swath, medium resolution (300 m at nadir) visible and near-infrared "Ocean Land Colour Instrument" (OLCI) spectroradiometer.

The Sentinel-3 mission is meant to be operational, so it has stringent revisit, coverage, and mission life cycle requirements (>15 years) that require the deployment of several satellites for each mission.

The first Sentinel-3 should be launched in 2013 (Sentinel 3A), and the second one (3B) in 2017. The OLCI is mostly based on the MERIS heritage but with 21 spectral channels instead of 15 and a fixed 12-degree across-track tilt that aims to minimize sun glint (1,300-km swath). One satellite can obtain global coverage within four days; two satellites can do so within two days.

The same principles previously used for MERIS radiometric and spectral calibration are used for Sentinel-3/OLCI, ensuring a high level of radiometric accuracy and stability.

The product suite includes all products already provided by MERIS plus some advanced products, such as inherent optical properties.

The Sentinel-3 data policy is dictated by the GMES data policy, i.e., free and open access to all data. The OLCI operational ground segment should be operated by EUMETSAT. Other entities will operate the decentralized "thematic" ground segment.

S-GLI

Sensor/Satellite	Agency	Launch Date	Swath	Resolution	Bands	Spectral Coverage (nm)
S-GLI/GCOM-C	JAXA (Japan)	2014	1,150-1,400	250/1,000	19	375-12,500

Sensor Description:

The Second-Generation Global Imager (S-GLI) will be flown as part of the Global Change Observation Mission for Climate research (GCOM-C) mission. This sensor is a follow-on to the GLI, a multi-spectral radiometer with 19 wavebands ranging from 375 to 12,500 nm. The 250-m spatial resolution aims at improving coastal ocean and aerosol observations.

Calibration:

Onboard calibrations will include a solar diffuser, internal lamp, lunar look by pitch maneuvers (for visible channels) and lunar through deep space window (for short wave channels), and dark current.[8]

[8] See http://www.ioccg.org/sensors/SGLI_mission_design_201002.pdf; accessed October 25, 2010.

The target for data accuracy of SGLI products is at the same level for GLI products (Murakami et al., 2006).

Data Availability:

Data products expected to be available online.[9]

Applications:

The S-GLI observations aim to improve our understanding of climate change mechanisms through long-term monitoring of aerosols, ocean color, derived phytoplankton and clouds, as well as vegetation and temperatures.

[9] See http://www.eorc.jaxa.jp.

COCTS-CZI

Sensor/Satellite	Agency	Launch Date	Swath	Resolution	Bands	Spectral Coverage (nm)
COCTS-CZI/HY-1C/D	CNSA (China)	2014	2,900/1,000	250/1,100	10/10	402-12,500/433-885
COCTS-CZI/HY-1E/F	CNSA (China)	2017	2,900/1,000	250/1,100	10/4	402-12,500/433-885

With the exception of the general specifications in the table above, the committee did not obtain additional information on the status or performance of the Chinese Ocean Colour and Temperature Scanner/Coastal Zone Imager (COCTS-CZI).

PACE and ACE

Sensor/Satellite	Agency	Launch Date	Swath	Resolution	Bands	Spectral Coverage (nm)
PACE	NASA (USA)	>2019	116.6 degree	1 km	26 spectral bands (5-nm resolution 350-775 nm)	350-2,135 nm

Sensor Description:

The Pre-Aerosol-Clouds-Ecosystem (PACE) and Aerosol-Cloud-Ecosystems (ACE) mission aim to advance research in ocean biology and biogeochemical cycles.

Calibration:

The need for direct lunar calibration, a vicarious calibration site, and global data for product validation are listed among the mission requirements.

Data Availability:

The data likely will be freely and openly available.

Applications:

The products derived from these sensors will be applied to research on the carbon cycle, marine ecosystem, phytoplankton physiology, near-shore and estuarine processes, and on physical-biological interactions.

Appendix B

Vicarious Calibration[1]

This appendix expands on the importance of a vicarious calibration. It provides the technical details associated with using Marine Optical Buoy (MOBY) for the ocean color vicarious calibration.

The following measurement equation is used to derive water-leaving radiance (L_w) (Franz et al., 2007):

$$L_t = [L_r + L_a + t_{dv}(L_f + L_w)t_{gv}t_{gs}f_p]$$

L: radiance;
t: transmittance;
L_t: spectral radiance at the satellite sensor;
L_r: Rayleigh contribution from the atmosphere;
L_a: aerosol contribution from the atmosphere (including Rayleigh-aerosol interactions);
L_f: sea-foam contribution;
t_{dv}: diffuse transmittance along the satellite-to-surface path ;
t_g: transmittance through gaseous absorption along the satellite-to-surface path;
t_s: the transmittance along the sun-to-surface path; and
f_p: accounts for the polarization dependence of the satellite sensor.

Sun glint is not included in the equation because these data would have been flagged under normal operations. All of these quantities depend on wavelength, and all but the L_w term can be determined from ancillary data (e.g., surface pressure is required to calculate L_r, wind speed for L_f, etc.) or, for L_a, through models combined with near-infrared measurements of the surface area that is being used for the vicarious calibration, in order to estimate the aerosol contribution at the blue-green spectral region of interest for the match-up dataset.

It is assumed that all quantities except L_w have zero uncertainty[2] and propagate uncertainties according to the International Organization for Standardization's (ISO) Guide to the Expression of Uncertainty in Measurement (GUM; ISO, 1993).

$$\frac{u(L_t)}{L_t} = \frac{u(L_w)}{L_w}\frac{1}{1+\dfrac{L_r + L_a + t_{dv}L_f}{L_w}} \cong \frac{u(L_w)}{L_w}\frac{L_w}{L_r + L_a + t_{dv}L_f}$$

The approximation follows because L_w is small compared to L_t, e.g., about 5 percent, and no more than 15 percent. So to achieve a relative uncertainty of 5 percent in L_w we need the sensor to be producing L_t values with a relative uncertainty of » 0.3 percent (=5 percent × 5/95). However, this level of uncertainty on a satellite sensor in orbit is not possible at the present time. It requires pre-flight calibration of sufficient accuracy, complete and robust instrument characterizations, and the ability to monitor any change in the response upon launch. One limit is the uncertainty in the standards of spectral radiance supplied by National Institute of Standards and Technology (NIST), which typically have an uncertainty of 0.5 percent (k = 2) in the visible region of the spectrum.

A stringent vicarious calibration is required to overcome the inability to constrain the sensor's uncertainty to 0.3 percent or less. To achieve this calibration, a natural source is selected as the surface reference site of L_w values, the site is instrumented with a robust, high-quality assured measurement facility, and the experiment is designed so as to

[1] Based on a white paper provided by C. Johnson, July 2010.

[2] Uncertainty can be classified as arising from random or systematic effects. Uncertainty values from random effects can generally be reduced by increasing the number of measurements; they scale as $1/\sqrt{N}$, where N is the number of measurements. For systematic effects, increasing the number of measurements has no impact whatsoever on the associated uncertainty values. Uncertainty values of either type are estimated as "standard uncertainties" corresponding to the estimated standard deviation (k = 1) and the combined uncertainty is the root-sum-square of the individual component values (assuming the values are uncorrelated). The GUM explains how to derive standard uncertainties for uncertainty estimates that can be evaluated statistically (Type A) and through other means (Type B).

minimize sources of bias and improve the data return (e.g., consideration of cloud cover probabilities).

The MOBY site has been used to calibrate ocean color sensors in the post-Coastal Zone Color Scanner (CZCS) era, and the requirements for ocean color vicarious calibration have been well documented (NASA, 2003). Here, we present the concept of random and systematic uncertainty and the measurement equation to support the role of a MOBY-like facility in ocean color research. First, in order to have acceptable values for the random components of uncertainty one can either have a broad distribution, or a narrow, well-defined distribution. The latter requires fewer samples to achieve the same uncertainty value. The well-defined, narrow distribution is found at the MOBY facility, with its stable marine atmosphere, central Pacific location, uniform oligotrophic waters, and robust instrument design that results in good measurement precision. An example of a broader distribution would be the BOUSSOLE or Aeronet-OC (Bailey et al., 2008). It can be argued that the best technical approach for vicariously calibrating a new satellite sensor such as VIIRS would be to have a precise, stable dataset so that the number of observations required to produce the asymptotic value of the random uncertainty component is as small as possible. The Ocean Biology Processing Group (OBPG) studied the effect of sample size on the uncertainty in the vicarious gain coefficient using MOBY for SeaWiFS; it concluded 45 to 60 samples would be required for reliable vicarious calibration of a stable sensor such as SeaWiFS (see Figure B.1).

Second, in order to have acceptable values for the systematic components of uncertainty, one needs a robust, well-characterized, high-quality assured dataset. Spectral biases cannot be tolerated at any level, because the bio-optical algorithms rely on band ratios. Unidentified or difficult to quantify bias introduced by the "atmospheric correction" (e.g., the process of estimating all the terms in the measurement equation except L_w) are mitigated by selecting sites where the atmospheric conditions and the marine environment are as simple as possible, the necessary ancillary data are available, and the models can be verified and improved upon. Likewise, the in situ instrument must be

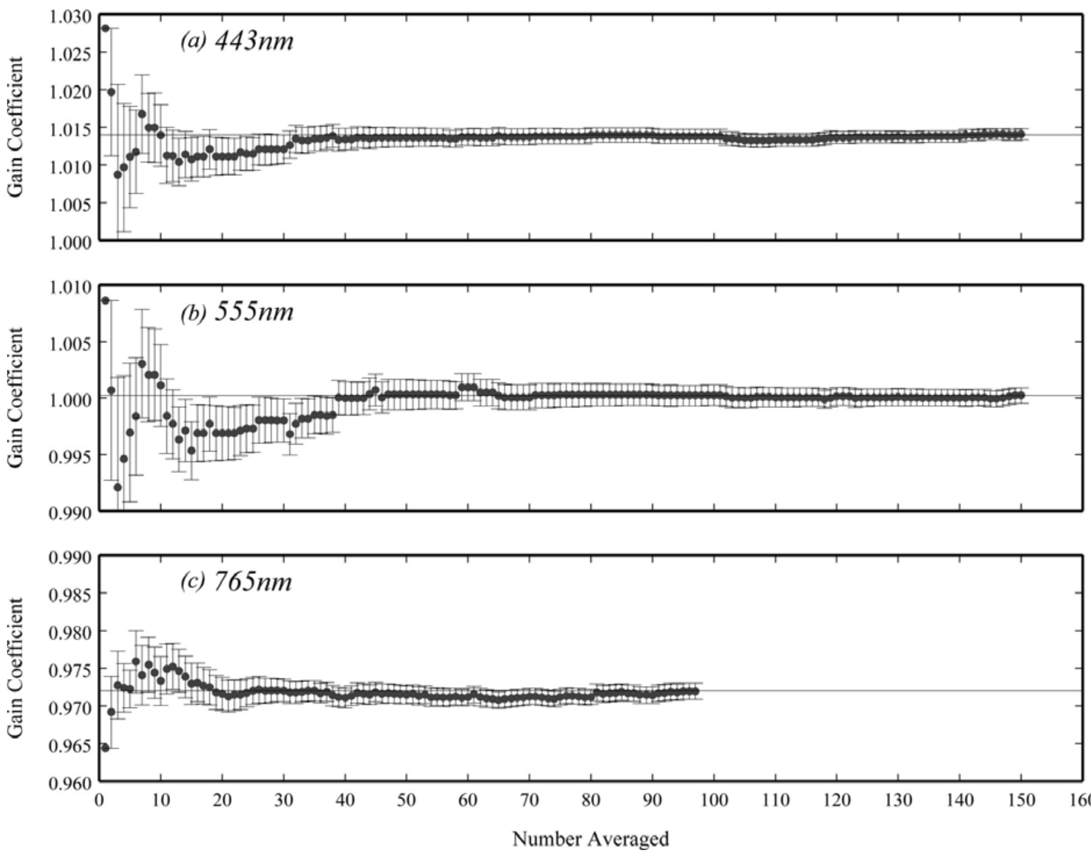

FIGURE B.1 Mean vicarious gains, g, derived for SeaWiFS bands at 443, 555, and 765 nm based on calibration samples between September 1997 and March 2006. Individual gains from the mission-long set of calibration match-ups were randomly sampled; growing the sample set one case at a time and averaging to show the effect of increasing sample size on g. Vertical error bars show the standard error on the mean at each sample size.
SOURCE: Franz et al., 2007; used with permission from the Optical Society.

fully characterized and supply values that are SI-traceable. The more robust this procedure, the more reliable is the final product. The MOBY project has gone to great effort to meet these objectives by incorporation of check standards, repeat calibrations, close linkage with NIST, expert and dedicated staff, good instrument design, and so forth. The evidence of the degree of the stability and precision of the MOBY products and the atmospheric correction procedures is demonstrated in Franz et al. (2007).

The MOBY site was selected to represent the majority of the observed natural sources—the open oceans. Coastal regions exhibit variations in L_w and the other terms in the measurement equation on many different temporal and spatial time scales compared to the MOBY site off Lanai, Hawaii. The sensor measures L_t, the proper interpretation of these data depend on thorough understanding of the sensor characterization (linearity, polarization, spectral out of band, etc.) and response to this top of the atmosphere radiant flux. A case could be made for additional sites, including coastal sites, with a MOBY-like site producing the basic calibration and the other equally robust sites, serving to explore the intricacies of the atmospheric correction methods, dark pixel assumptions, and the satellite sensor characterization functions themselves.

In conclusion, study of the measurement equation and robust experimental design establishes that the MOBY approach and its uncertainty values are necessary for productive ocean color research. An examination of the uncertainty in upwelling spectral radiance for MOBY is given in Brown et al. (2007), where the Type A random uncertainty was estimated to be 1 percent. Franz et al. (2007) state that without the vicarious calibration provided by MOBY, the bias in L_{wn} resulting from the errors in the pre-flight calibration for SeaWiFS would have been 25 percent at 490 nm and 75 percent at 412 nm and the mean C_a retrieval would be biased low by 25 percent.

Appendix C

Comprehensive Oceanic and Atmospheric Optical Datasets

Some past data collection campaigns have been designed only for validation of specific products without regard for subsequent possible uses and long-term value of the data. This results in a partial dataset, which, when later examined for other purposes, lacks one or more crucial "missing pieces" that preclude its use.

A comprehensive dataset has all the information necessary for a complete radiative transfer (RT) calculation to propagate sunlight from the top of the atmosphere (TOA), through the atmosphere to the sea surface, through the sea surface into the water, and then from the water back to the atmosphere, and finally through the atmosphere to the sensor. This RT process is the physical basis for all ocean color remote sensing and must be fully understood when evaluating the performance of any particular sensor and the products it generates.

Another way to summarize the necessary information is to keep in mind that to validate an environmental parameter or ocean color product (such as the chlorophyll or Colored Dissolved Organic Matter [CDOM] concentration, or depth and bottom type in shallow water), it first is necessary to validate the atmospheric correction algorithm, which requires knowing the absorbing and scattering properties of the atmosphere. To validate the bio-optical inversion algorithm that retrieves an ocean color product from the sea-level remote sensing reflectance, it is necessary to know both the value of the product and the water-leaving radiance. To understand how the product influences the water-leaving radiance, it is necessary to know the water absorbing and scattering properties (the inherent optical properties [IOPs]) and the in-water radiance distribution.

RT models are presently validated to the extent possible with incomplete datasets. In such exercises, the available IOP measurements plus reasonable assumptions about the missing pieces are used as inputs. The model predictions are then compared with the available radiometric measurements. However, there are always too many missing inputs and outputs to claim rigorous and complete model validation. Consequently, verification of a given model against independently developed numerical models becomes an expedient substitute for rigorous and complete model validation (e.g., Mobley et al., 1993).

The lack of comprehensive datasets is understandable given agency funding constraints for personnel, instrumentation, and ship time. Unfortunately, data collection for its own sake is almost never viewed as fundable science, even though model and algorithm development and validation always need comprehensive datasets. Finally, there are instrument limitations for measurement of some needed parameters. Nevertheless, the collection of even a few comprehensive datasets for selected water and atmospheric conditions would greatly advance ocean color remote sensing and environmental optics in general.

In addition to collecting the data needed for model and algorithm validation, data collection programs should be viewed as opportunities to compare various instruments and methodologies for making the same kind of measurement. Measurement redundancy is absolutely necessary in a field experiment.

The necessary measurements are dictated by the inputs needed to solve the radiative transfer equation (RTE) and to validate its output. Conceptually, atmospheric and oceanic absorbing and scattering properties + boundary conditions $\rightarrow$ RTE $\rightarrow$ radiance $\rightarrow$ other optical quantities of interest.

To validate a model or algorithm at one point and one time, simultaneous and co-located measurements are needed for the following quantities:

Oceanic Measurements

In principle, the two fundamental IOPs should be measured. See *Light and Water* (Mobley, 1994) or similar texts for a complete discussion of the quantities discussed here. These are the:

- absorption coefficient $a(z,\lambda)$, measured as a function of depth z and wavelength λ.
- volume scattering function VSF(z,λ,ψ); ψ is the scattering angle, 0-180 degree.

What can be measured today:

Commercial instruments are available for in situ absorption measurements, and promising new instruments are under development.

No commercially produced instruments are currently available for in situ measurement of the VSF over the full range of scattering angles, but several unique instruments exist. Others are under development. Bench-top commercial instruments exist for measurements made on water samples. Given the current lack of readily available in situ VSF instruments, a reasonable proxy is to measure:

- the beam attenuation coefficient $c(z,\lambda)$, measured as a function of depth and wavelength.
- the backscatter coefficient $b_b(z,\lambda)$, measured as a function of depth and wavelength.

Commercial instruments are available for in situ measurement of beam attenuation, although (as with many measurements) there are instrument design issues that require standardization (Boss et al., 2009). The same is true for measurement of the backscatter coefficient.

Measurement of c allows the scattering coefficient b to be obtained from $b(z,\lambda) = c(z,\lambda) - a(z,\lambda)$. Knowing the scattering and backscatter coefficients allows the scattering phase function to be estimated from $b_b(z,\lambda)/b(z,\lambda)$, which can give acceptable inputs to the RTE (Mobley et al., 2002).

Boundary Conditions Needed to Solve the RTE

In principle the needed measurements are:

- the in-air, sea-level downwelling (sun and sky) radiance L_d(in air,θ,ϕ,λ) as a function of direction (polar angle q and azimuthal angle ϕ) and wavelength.
- the sea surface wave spectrum.
- the bidirectional reflectance distribution function, BRDF$(\theta',\phi',\theta,\phi,\lambda)$, of the bottom, if not infinitely deep water, as a function of all incident (θ',ϕ') and reflected (θ,ϕ) directions and wavelength.

What can be measured today:

Although these boundary conditions can be measured, they are almost never measured in the field because of instrument limitations. Therefore, it is reasonable to measure the following:

- the above-water, downwelling plane irradiance E_d(in air,λ) incident onto the sea surface, which can and should be partitioned into direct and diffuse contributions (Gordon, 1989).
- sun zenith angle (or compute from latitude, longitude, date, and time).
- sky and cloud conditions.
- wind speed.

Bottom irradiance reflectance $R_b(l) = E_u(l)/E_d(l)$ can be used along with the assumption that the BRDF is Lambertian to obtain satisfactory predictions of water-leaving radiance for most remote sensing purposes (Mobley et al., 2003).

In-Water Outputs

Ideally, the following should be measured for comparison with RT model predictions:

- the full radiance underwater distribution $L(z,\theta,\phi,\lambda)$ as a function of depth, direction, and wavelength.
- the irradiances, $E_d(z,\lambda)$, $E_u(z,\lambda)$, and $E_o(z,\lambda)$, which give a consistency check by integrating the radiance to compare with the irradiances.
- the in-air upwelling radiance L_u(in air,θ,ϕ,λ).

What can be measured today:

There are no commercial instruments for in situ measurement of the full radiance distribution, although a few unique instruments do exist (Voss and Chapin, 2005). Commercial instruments are available for E_d and E_u, which are routinely measured. Commercial instruments are available for radiance measurements in a given direction, so radiance is usually measured only for selected directions (most commonly the upwelling direction, which can be used in estimating the remote sensing reflectance R_{rs}). An acceptable set of radiometric measurements is then:

- the upwelling (nadir-viewing), in-water radiance $L_u(z,\lambda)$.
- the upwelling and downwelling in-water plane irradiances, $E_d(z,\lambda)$ and $E_u(z,\lambda)$.
- the above-water upwelling radiance in one direction, e.g., L_u(in air,q=40,f=135,λ). The recommended direction is at 40 deg off-nadir and at 135-degree relative to the sun, which minimizes the sun glint (Mobley, 1999).
- the in-air downwelling (sky) radiance in the reflection direction, e.g., L_d(in air,q=40,f=135,λ), plus a gray-card measurement for estimation of E_d and R_{rs} (the so-called Carder method of estimating R_{rs}; see Mobley, 1999).
- the downwelling in-air plane irradiance, E_d(in air, λ) for both direct and diffuse lighting.

Ancillary Measurements

These measurements are not needed to solve the RTE, but they are necessary for validation of bio-optical algorithms for retrieval of Chl, CDOM, TSM, etc. They also are needed to understand the fundamental connections between water column constituents and inherent optical properties. In principle, the following should be measured:

- Phytoplankton pigments (at the minimum, measure Chl-a).
- Absorption coefficient $a(z,\lambda)$ partitioned into the contributions by water, phytoplankton, CDOM, organic, and inorganic particles. At the minimum use filtered and unfiltered instruments to partition the absorption into dissolved and particulate contributions.
- The VSF(z,λ,ψ) (or total scattering and backscattering) partitioned into contributions by water, phytoplankton, and minerals (assuming CDOM is non-scattering). Chlorophyll-a is often the only pigment measured. Filtered and unfiltered instruments can be used to partition absorption into particulate and dissolved fractions. Partitioning the VSF into component concentrations is almost never done.

Atmospheric Measurements

To solve the RTE in the atmosphere, the same inputs are needed as for the ocean, viz. the atmospheric absorption and scattering properties and sea surface boundary conditions. However, these IOPs are usually cast in a different form, using a different vocabulary. The vastly greater path lengths needed for atmospheric attenuation measurements precludes the development of instruments that can directly measure the needed IOPs. The measurements that can and should be made are the following:

- Sea-level pressure, temperature, humidity, and wind speed. These are standard meteorological measurements that allow the Rayleigh scattering contribution to the atmospheric path radiance to be calculated.
- Atmospheric gas contributions to absorption are known for gases whose mixing ratios are constant. Ozone and water vapor concentrations are highly variable and need to be determined for detailed atmospheric RT calculations.

Aerosol concentration and optical properties are highly variable and remain the source of the greatest uncertainty in atmospheric RT calculations and atmospheric correction. The standard measurement used to deduce aerosol properties is sun photometry using, for example, the CIMEL sun photometer (the Aeronet, from which it is possible to extract the needed aerosol properties [Wang and Gordon, 1993; Dubovik and King, 2000]), which are:

- aerosol optical depth $\tau(\lambda)$ as a function of wavelength.
- aerosol scattering phase function.
- aerosol albedo of single scattering $\omega_o(\lambda)$ (= b/c, so related to the absorption and scattering coefficients).

If highly accurate atmospheric RT calculations are to be performed, vertical profiles of temperature, water vapor, and cloud type should be measured (typically with balloon-borne instruments or ground-based LIDAR). Ozone concentration should be determined from ancillary data such as sea-level measurements or satellite observation (e.g., the TOMS sensor) if RT calculations are to be done below 350 nm. Ozone can be optically important also in the visible part of the spectrum (the wide Chappuis band in the green wavelengths). In particular, the variations in the O_3 column content have to be accounted for when processing ocean color data, and the green signal (550-560 nm) corrected accordingly. It has also been demonstrated that nitrogen oxide may affect the blue channels.

Polarization

Polarization is an inherent feature of all electromagnetic radiation, including ocean color radiance. However, the ocean color community has usually ignored polarization with a few notable exceptions such as the POLDER satellite. This is both because of measurement difficulties and because unpolarized measurements can yield acceptably accurate answers for many (but not all) problems of interest. However, polarization carries information that can be exploited to improve ocean color product retrievals. For example, surface reflection is strongly dependent on polarization, so that sun glint is partially polarized, depending on the relative sun and viewing directions. In addition, biological and mineral particles have different indices of refraction and different size distributions, and thus scatter light differently, including polarization changes during the scattering. The French POLDER satellite exploited these effects to improve retrievals of biological vs. mineral particulate loads in the water.

Some atmospheric RT codes now include polarization (e.g., 6SV; Vermote et al., 2006), and a few researchers have developed proprietary coupled ocean-atmosphere RT codes. Polarization likely will become more important in future OCR applications. Therefore, the above measurements should be made with polarization in mind. Inclusion of polarization effects in RT computations requires the following measurements:

- Instead of the VSF (z,λ,ψ), measure the full Mueller matrix. The Mueller matrix has 16 elements, although not all are independent. The (1,1) element is the VSF.
- Instead of the radiance L, measure the Stokes Vector (4 elements).

There are currently no instruments for in situ measurement of the Muller matrix, although one measurement of the full matrix has been made in the laboratory on a sea water sample (Voss and Fry, 1984). Instruments are under development for measurement of selected elements of the Muller matrix, which if available would enable underwater polarized RT calculations to be made for three elements of the Stokes Vector.

Unique instruments do exist for underwater measurement of the Stokes Vector (Tonizzo et al., 2009). Although such measurements are not yet common, they likely will become more so in the future.

Doing unpolarized radiative transfer in both the ocean and the atmosphere and using scalar (unpolarized) RT codes results in errors in the order of 10 percent in predictions of TOA radiances as needed for development and validation of satellite sensors and atmospheric corrections algorithms. The magnitude and wavelength dependence of the errors depend on the atmospheric and oceanic properties, sun angle, and viewing direction. The errors therefore cannot be quantified without detailed vector (polarized) RT calculations for the particular environmental and viewing conditions of interest. Therefore, the development of a user-friendly and publicly available coupled ocean-atmosphere vector RT code would greatly benefit future ocean color sensor and algorithm development.

Appendix D

Commercial GEO-Satellite Hosted Remote Sensing

Dramatic GEO remote-sensing cost reduction is being demonstrated by the Commercially Hosted Infrared Payload (CHIRP) program, a U.S. Air Force (USAF) research and development (R&D) effort scheduled for launch late 2011. Gary Payton, USAF Undersecretary, noted in October 2008 (Brinton, 2008): "The deal . . . was fantastic . . . a fourth-of-the-world view on orbit at geosynchronous, and a year . . . of downlink data . . . for less than the cost of a launch vehicle." Per U.S. Department of Commerce Office of Space Commercialization[1]: "The Air Force expects to achieve major cost savings by flying this mission as a hosted payload. They estimate it would cost approximately $500 million to launch a dedicated free flyer to satisfy 100 percent of the technical questions associated with the experiment. The hosted payload ended up costing $65 million and should satisfy 80 percent of the technical questions."

Moreover, if CHIRP is launched in CY2011, then program duration from July 2008 contract inception to initial operational configuration (IOC) will have been just three years. As is often the case with developmental remote sensing missions, CHIRP has been paced by sensor progress. The original launch date was in mid-CY2010, but the sensor delivery date slipped. Unlike a dedicated mission, however, it was possible to shift to another satellite. This reduced much of the cost growth that might otherwise have dramatically increased expenditures—cf. sensor delay impacts to the Geostationary Operational Environmental Satellite "R" Series (GOES-R) and the former National Polar-orbiting Operational Environmental Satellite System (NPOESS) mission costs. The CHIRP program delay underscores an advantage of Group on Earth Observations (GEO)-hosting: Many host opportunities.

There are 100-plus commercial telecommunications satellites in GEO, each with a nominal 15-year life. Therefore, six must be replaced each year just to maintain operations, much less to grow capability. The reality is better. As shown in Figure D.1 (FAA, 2009), on average about 20 commercial satellites were launched annually to 2009, and that trend is expected to continue for the next decade. A commercial GEO satellite host opportunity appears at least monthly, on average.

Once a sensor is assigned to a satellite, then the sensor must be ready on the satellite's schedule to be hosted by that satellite. If the sensor is delayed, then it is "off-ramped" from the originally specified satellite host, and later "on-ramped" to a subsequent satellite host. Considering the number of satellites launched each year, it is likely a new host can be found soon that will launch on a schedule compatible with the sensor delay. Moreover, while mission cost will rise to accommodate the sensor delay and modifications to a new host satellite, the commercially hosted mission can avoid much of the "marching army" costs associated with a delayed dedicated satellite mission. The commercial hosting option therefore offers dramatically lower cost than a dedicated satellite mission with surprising schedule flexibility and almost no data rate limitation other than the cost of renting sufficient transponder capacity.

However, main hosted-sensor trade-offs need to be considered, such as, the risk of a non-optimal host GEO longitude, and less control over the host satellite compared to a dedicated mission. Satellite location and operations are driven by the primary commercial telecommunications markets served by the satellite. Selecting a host based on its anticipated operational longitude includes the risk that the satellite operator may later place the satellite at a different longitude, either before launch or after operations at the originally planned longitude. The satellite operator also typically will not allow a hosted sensor to drive satellite maneuvers, though the operator can maneuver the satellite for sensor purposes with advance notice and coordination.

[1] See http://www.space.commerce.gov/general/commercialpurchase/hostedpayloads.shtml.

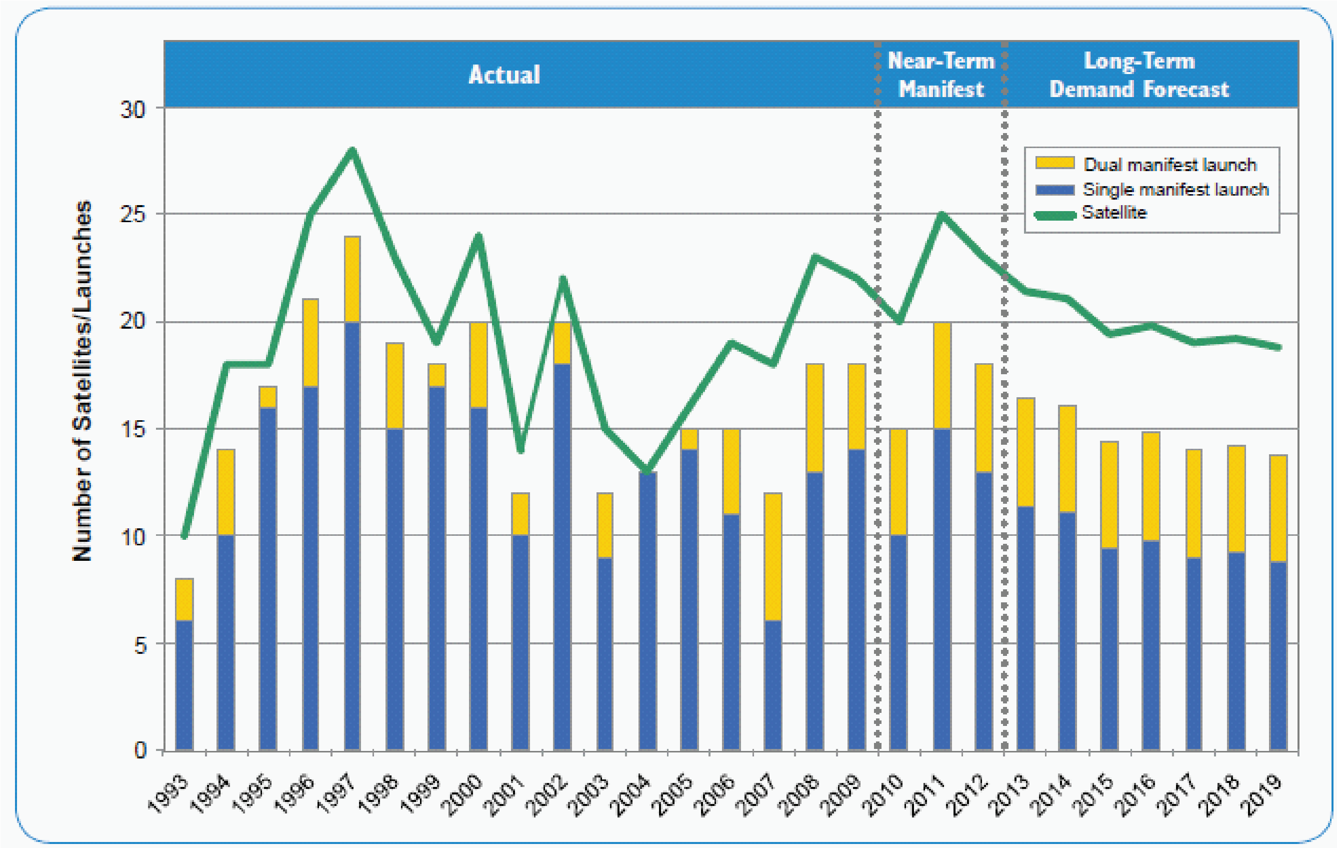

FIGURE D.1 Satellite and launch demand realized and forecast for the years 1993-2019. A dual manifest launch can launch two satellites at once. The green line depicts how many satellites were launched or are predicted to launch per year. On average, 20 commercial GEO satellites were launched each year to 2009, and this trend is expected to continue.
SOURCE: FAA, 2009.

Hosted GEO Ocean Color?

Combining the information from the Korean COMS-1 Geostationary Ocean Color Imager (GOCI) and the CHIRP mission suggests a potentially attractive GEO ocean color option. Coastal Waters Imaging (CWI) spectral requirements are not substantially tighter in bandwidth than GOCI and the CWI signal-to-noise (SNR) requirements are comparable to GOCI (NOAA, 2004; Faure, 2007). Therefore, CWI requirements suggest sensor dimensions (and mass) would be comparable to GOCI, as optical aperture and SNR are the primary sensor dimensional drivers. As GOCI mass is within the capacity of a commercial GEO satellite, CWI capability may be practical within the dimensions, mass, power, and data rate envelope for cost-effective commercial GEO hosting.

Appendix E

Acronyms

ACE	Aerosol-Cloud-Ecosystems
AVHRR	Advanced Very High Resolution Radiometer
AVIRIS	Airborne Visible InfraRed Imaging Spectrometer
BOUSSOLE	Bouée pour l'acquisition de Séries Optiques à Long Terme
CALIPSO	Cloud-Aerosol LIDAR and Infrared Pathfinder Satellite Observation
CCI	Climate Change Initiative
CCMA	Center for Coastal Monitoring and Assessment
CDOM	Colored Dissolved Organic Matter
CDR	Climate Data Records
CEOS	Committee on Earth Observation Satellites
CHIRP	Commercially Hosted InfraRed Payload
CMA	China Meteorological Administration
CNES	Centre National d'Etudes Spatiales
CO_2	Carbon Dioxide
COCTS	Chinese Ocean Colour and Temperature Scanner
COMS	Communications Oceanography and Meteorology Satellite
CONUS	Contiguous United States
CWI	Coastal Waters Imaging
CZCS	Coastal Zone Color Scanner
CZI	Coastal Zone Imager
DOC	Dissolved Organic Carbon
DOD	Department of Defense
ECV	Essential Climate Variables
EDR	Environmental Data Record
ENSO	El Niño Southern Oscillation
ENVISAT	Environmental Satellite
EOS	Earth Observing System
ESA	European Space Agency
ESL	Expert Support Laboratory
FOV	Field-Of-View
GCOM	Global Change Observation Mission
GCOM-C	Global Change Observation Mission for Climate Research
GCOS	Global Climate Observing System
GEO	Geostationary Earth Orbit
GEO	Group on Earth Observations
GEOCAPE	Geostationary Coastal and Air Pollution Events
GHRSST	Group for High-Resolution Sea Surface Temperature
GLAS	Geoscience Laser Altimeter System
GLI	Global Imager
GMES	Global Monitoring for Environment and Security
GOCI	Geostationary Ocean Color Imager
GOES	Geostationary Operational Environmental Satellite
GOES-R	Geostationary Operational Environmental Satellite "R" Series
GSD	Ground Sample Distance
GSFC	Goddard Space Flight Center
GUM	Guide to the Expression of Uncertainty in Measurement
HAB	Harmful Algal Bloom
HICO	Hyperspectral Imager for the Coastal Ocean
HyspIRI	Hyperspectral Infrared Imager
IFA	Integrated Filter Assembly
IOC	Initial Operational Configuration

IOCCG International Ocean Colour Coordinating Group
IOP Inherent Optical Properties
IPO Integrated Program Office
ISO International Organization for Standardization
ISRO Indian Space Research Organization
ITAR International Traffic in Arms Regulations

JAXA Japan Aerospace Exploration Agency
JPL Jet Propulsion Laboratory
JPSS Joint Polar Satellite System

LED Light-Emitting Diodes
LEO Low Earth Orbit
LIDAR LIght Detection And Ranging
LMR Living Marine Resources

MERIS Medium-Resolution Imaging Spectrometer
MERSI Medium Resolution Spectral Imager
MOBY Marine Optical Buoy
MODIS Moderate Resolution Imaging Spectroradiometer
MTF Modulation Transfer Function

NASA National Aeronautics and Space Administration
NCDC National Climate Data Center
NESDIS National Environmental Satellite, Data, and Information Service
NGAS Northrop Grumman Aerospace Systems
NIR Near-Infrared
NIST National Institute of Standards and Technology
NMFS National Marine Fisheries Service
NOAA National Oceanic and Atmospheric Administration
NOMAD NASA bio-Optical Marine Algorithm Dataset
NOS National Ocean Service
NPOESS National Polar-orbiting Operational Environmental Satellite System
NPP NPOESS Preparatory Project
NRL Naval Research Laboratory
NRT Near-Real Time
NSF National Science Foundation

OBB Ocean Biology and Biochemistry
OBPG Ocean Biology Processing Group
OCM Ocean Colour Monitor
OCM-2 Ocean Colour Monitor on-board Oceansat-2
OCR Ocean Color Radiance
OCR-VC Ocean Colour Radiometry Virtual Constellation
OCTS Ocean Color and Temperature Scanner
OES Ocean Ecology Spectrometer
OLCI Ocean Land Colour Instrument
ONR Office of Naval Research
OOB Out-of-Band

PACE Pre-Aerosol-Clouds-Ecosystems
PAR Photosynthetically Available Radiance
PIC Particulate Inorganic Carbon
POC Particulate Organic Carbon
POLDER Polarization and Directionality of the Earth's Reflectances
PRISM Portable Remote Imaging SpectroMeter

R&D Research and Development
RSR Relative Spectral Response
RT Radiative Transfer
RTE Radiative Transfer Equation

SAB Scientific Advisory Board
SCIAMACHY SCanning Imaging Absorption spectroMeter for Atmospheric CartograpHY
SEADAS SeaWiFS Data Analysis System
SeaWiFS Sea-viewing Wide Field-of-view Sensor
SIMBIOS Sensor Intercomparison and Merger for Biological and Interdisciplinary Oceanic Studies
S-GLI Second-Generation Global Imager
SNR Signal-to-Noise Ratio
SOA State Ocean Administration
SST Sea Surface Temperature
SWIR Short Wave Infrared

TOA Top of Atmosphere
TZCF Transition Zone Chlorophyll Front

USAF U.S. Air Force
UV Ultraviolet

VIIRS Visible Infrared Imager Radiometer Suite
VIS Visible Spectrum
VNR Visible and Near-Infrared Radiometer

Appendix F

Committee and Staff Biographies

COMMITTEE

James A. Yoder *(Chair)* is Vice President for Academic Programs and Dean at the Woods Hole Oceanographic Institution (WHOI). A biological oceanographer, Dr. Yoder is well known in the oceanographic research community, having served as a researcher, professor, and more recently as Director of the Division of Ocean Sciences at the National Science Foundation in Washington, D.C., from 2001 to 2004. He has worked at NASA headquarters and has been a member of numerous national and international committees and panels on oceanographic research. In particular, he was chair of the International Ocean-Colour Coordinating Group. Dr. Yoder received a B.A. degree in botany from DePauw University in 1970, and M.S. and Ph.D. degrees in oceanography from the University of Rhode Island (URI) in 1974 and 1979, respectively. He joined the staff at the Skidaway Institute of Oceanography in Georgia in 1978, and from 1986 to 1988 was a visiting senior scientist at the Jet Propulsion Laboratory, working as a program manager in the ocean branch at NASA headquarters. He joined the faculty at the Graduate School of Oceanography (GSO) at URI in 1989 and was promoted to professor in 1992. He was named Associate Dean of Oceanography at GSO in 1993 and served in that capacity until 1998, with responsibilities for curriculum planning and delivery, admissions, recruitment, and graduate student affairs. Dr. Yoder has served on NRC committees and currently is a member of the Ocean Studies Board.

David Antoine is a CNRS senior research scientist at the Marine Optics and Remote Sensing group of the Laboratoire d'Océanographie de Villefranche in France. He received a doctorate degree in oceanography from the Université Pierre and Marie Curie in Paris, France, in 1995. His research interests include marine optics, bio-optics, radiative transfer and applications, ocean color remote sensing including atmospheric corrections, and modeling of oceanic primary production from satellite ocean color. He was involved in the definition, preparation, and implementation of the European Space Agency (ESA) ENVISAT-MERIS ocean color satellite mission. He has served as chair (2007-2009) of the ocean group of the French space agency (CNES) scientific committee. He now serves as chair of the International Ocean-Colour Coordinating Group, and is a member of ESA's Earth Science Advisory Committee.

Carlos E. Del Castillo is a member of the Senior Professional Staff with the Space Department of the Johns Hopkins University Applied Physics Laboratory, and is the William S. Parsons Professor at the Johns Hopkins University Department of Earth and Planetary Sciences. Dr. Del Castillo started his career at the University of Puerto Rico studying the effects of oil pollution in tropical marine environments. Later, at the University of South Florida, his interest in organic carbon biogeochemistry and the carbon cycle led him to the use of remote sensing to study biogeochemical and physical processes in the ocean through a combination of remote sensing and field and laboratory experiments. While working at NASA as a researcher, Dr. Del Castillo also served as Project Manager at Stennis Space Center, MS, and as a Program Scientist at NASA Headquarters. Dr. Del Castillo served in several inter-agency working groups, chaired NASA and National Science Foundation workshops, and is now a member of NASA's Carbon Cycle and Ecosystem Management and Operations Working Group. Dr. Del Castillo has several well-cited publications (more than 70 citations), co-edited a book on the application of remote sensing techniques, and is a frequent reviewer for technical journals. He received a B.S. in biology and an M.S. in marine chemistry from the University of Puerto Rico, Mayaguez, and his Ph.D. in oceanography from the University of South Florida.

Robert H. Evans is a research professor at the University of Miami Rosenstiel School of Marine and Atmospheric Sciences (RSMAS). Dr. Evans is a faculty member of the RSMAS Remote Sensing Group (RSG), an interdisciplinary research group engaged in research and graduate instruction in the techniques of satellite oceanography and their application to problems in physical, biological, and chemical oceanography. Dr. Evans' focus of research is to develop quantitative methods that permit timely access to satellite remote sensing observations of transient events in the ocean, using imaging infrared sensors and multi-spectral infrared and color scanner observations. He continues evolutionary development of processing and analysis capabilities with the goal of generating long-term time-series of oceanic mesoscale variability.

Curtis Mobley is the Vice President for Science and Senior Scientist at Sequoia Scientific, Inc. Dr. Mobley has a background in physics and meteorology, but most of his career has been devoted to research in radiative transfer theory applied to problems in optical oceanography. He created the widely used *HydroLight* computer program and wrote the textbook *Light and Water: Radiative Transfer in Natural Waters*. Early in his career he was a Fulbright Fellow in Germany, and has held both regular (at the National Oceanic and Atmospheric Administration Pacific Marine Environmental Laboratory) and senior (at the Jet Propulsion Laboratory) National Research Council Resident Research Associateships. He was an oceanographer with the University of Washington Joint Institute for the Study of the Atmosphere and Ocean during the 1980s. From 1989 to 1991, he was the Program Manager of the Ocean Optics (now Littoral Sciences and Optics) program at the Office of Naval Research. Dr. Mobley has been an associate professor of physics at Pacific Lutheran University and is now an Affiliate Professor in the School of Oceanography at the University of Washington.

Jorge L. Sarmiento is the George J. Magee Professor of Geosciences and Geological Engineering at Princeton University. He obtained his Ph.D. at the Lamont-Doherty Geological Observatory of Columbia University in 1978, then served as a postdoctoral fellow at the Geophysical Fluid Dynamics Laboratory/NOAA in Princeton before joining the Princeton University faculty in 1980. He has published widely on the global carbon cycle, the use of chemical tracers to study ocean circulation, and the impact of climate change on ocean biology and biogeochemistry. He has participated in the scientific planning and execution of many of the large-scale multi-institutional and international oceanographic biogeochemical and tracer programs of the past three decades. He was Director of Princeton's Atmospheric and Oceanic Sciences Program from 1980 to 1990 and 2006 to the present, and is Director of the Cooperative Institute for Climate Science. He has served on the editorial board of multiple journals and as editor of *Global Biogeochemical Cycles*. He is a Fellow of the American Geophysical Union and the American Association for the Advancement of Science.

Shubha Sathyendranath is a Senior Scientist at the Plymouth Marine Laboratory (UK) and an Adjunct Professor at Dalhousie University (Canada). She served as Executive Director of the Partnership for Observation of the Global Oceans (POGO) until 2008 and continues to be involved in POGO, currently focusing on its capacity building efforts. She is an expert in marine optics and has several years of experience working on ocean color algorithm development and applications, and has published extensively in this field. She earned a doctorate in Optical Oceanography from the Université Pierre and Marie Curie in Paris, France, in 1981. Dr. Sathyendranath is a former member of the National Academies' Committee on International Capacity Building for the Protection and Sustainable Use of Oceans and Coasts.

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Art Charo has been a Senior Program Officer at the NRC's Space Studies Board since 1995. During this time, he has directed studies that have resulted in some 33 reports, notably the first NRC "decadal surveys" for solar and space physics (2002) and for Earth science and applications from space (2007). Dr. Charo received his Ph.D. in physics from Duke University in 1981 and was a post-doctoral fellow in chemical physics at Harvard University from 1982 to 1985. He then pursued his interests in national security and arms control at Harvard University's Center for Science and International Affairs, where he where he was a fellow from 1985 to 1988. From 1988 to 1995, he worked as a senior analyst and study director in the International Security and Space Program in the Congressional Office of Technology Assessment (OTA). Dr. Charo is a recipient of a MacArthur Foundation Fellowship in International Security (1985-1987) and a Harvard-Sloan Foundation Fellowship (1987-1988). He was the 1988-1989 American Institute of Physics AAAS Congressional Science Fellow. His publications include research papers in molecular spectroscopy; reports for OTA on arms control, Earth remote sensing, and space policy; and a monograph, *Continental Air Defense: A Neglected Dimension of Strategic Defense* (University Press of America, 1990).

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