Ocean Color Climate Data Records Workshop Report

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I. Background

As stated by the National Research Council (NRC) in its report on "Climate data records for environmental satellites", NOAA's new mandate to understand climate variability and change imposes requirements for the generation and preservation of Climate Data records (CDRs) that are significantly different from traditional weather forecast data records (NRC, 2004). For this reason, a new set of tasks and structures will need to be implemented within NOAA to ensure the acquisition, processing, long term archiving, and distribution of CDRs.

Satellite based remote sensing observations have provided the means to assess physical and biological changes in the surface of the oceans on local, regional and basin scales. Oceans cover 70% of the earth surface and, as a result of their circulation, play a major role in the spatial and temporal distribution of weather patterns, the production of natural resources, and the large-scale transport and storage of greenhouse gases. For example, marine physical, chemical, and biological processes are responsible for the removal of carbon dioxide (CO_2) from the atmosphere in certain regions and its release in others (Brewer et al. 1989; Sarmiento et al. 2000). The global rates of marine CO_2 sequestration (i.e. the balance between global atmospheric removal and release) and the rates of transport are a function of both ocean circulation and biological activity.

Upwelling regions, such as the coast off Peru (Humboldt Current), Namibia (Benguela Current), and the western United States (California Current), can represent large sources or sinks for CO_2 (Hales, 2005). Furthermore, these regions have long been recognized as areas of high marine productivity, sustaining large fisheries and concomitant commercial activities. However, primary productivity and the rate of air-sea gas exchange depend on upwelling strength which is a function of ocean circulation and coastal wind patterns. And, because these forcings experience significant seasonal and interannual variability, long-term changes in atmospheric patterns may significantly alter oceanographic processes and their effects on a regional scale (Chavez et al. 2003). Thus, we need to characterize the feedback mechanisms between weather, ocean circulation, and ecosystem dynamics at different spatial and temporal scales if we are to understand the effects that climate change will have on marine biological productivity, the distribution of biological resources, and long term alteration in air-sea gas exchange rates at regional and global scales.

To this end, the use of satellite-derived oceanographic observations provides the means to characterize large-scale seasonal, interannual, and decadal spatial changes in physical and biological sea surface properties. These changes can then be statistically coupled to long-term changes in atmospheric patterns to assess the sensitivity of oceanic processes to climate change. Satellite-based oceanographic observations provide unique regional and basin-scale datasets that can be used to test and improve our climate models and constrain error estimates in our forecasts. Furthermore, satellite based observations have provided the oceanographic community with the tools to study large scale dynamics of pelagic ecosystem (Abbott and Zion 1985, Gregg et al. 2005). Hence, ocean color CDRs will play a key role in NOAA's response to its charge to "understand and predict changes in the Earth's environments and conserve and manage coastal and marine resources to meet the Nation's economic, social, and environmental needs". Some of NOAA's climate science applications include:

- Marine ecosystem changes and the potential effects on commercial fisheries
- Changes in the role of the oceans in carbon cycling and CO_2 sequestration

Over the past two decades, NASA's efforts to acquire ocean color remote sensing time-series through radiometric measurements from satellites have provided the means to characterize seasonal and interannual regional and basin scale variability in the optical properties of the marine environment, chlorophyll concentration, and ocean primary productivity (Gregg et al. 2005). The extension in time of these ocean color data records will provide the basis for the generation of ocean color CDRs. However, we first need to develop a consensus among the scientific community with respect to which ocean color products are of direct relevance to ecosystem and climate research.

We further need to define clearly the requirements for the generation of CDRs, including requirements for sensor design, calibration and characterization, as well as the processing, reprocessing, storage, and distribution of the data. In this context, previous and ongoing satellite ocean color missions from NASA have provided significant lessons regarding the need for continuous sensor calibration, validation, and algorithm refinement. In contrast with the operational nature of NOAA's weather satellite, CDRs require not only a detailed pre-launch characterization of the sensor, but also vicarious calibration monitoring, and satellite to satellite cross calibrations. At present, ocean color remote sensing missions have developed a set of protocols for sensor calibration that include on-board lunar and solar calibration, as well as the Marine Optical BuoY (MOBY) which supports in situ measurements for vicarious calibration. In addition, NASA, through its SIMBIOS program, provided the support for an initial effort to merge ocean color time-series from different missions, including SeaWiFS, ADEOS-I, and MODIS-Terra. These programs, and the lessons learned from them, should help direct NOAA in its effort to generate ocean color CDRs.

In order to advise NOAA on the steps that must be taken to ensure the generation of ocean color remote sensing that meet the requirements to support climate research, we requested the input from the scientific community during a workshop held at Oregon State University on August 2005. This scientific panel, composed of representatives from NOAA Climate Office, NESDIS and NMFS, NASA Ocean Color Research Group, NPOESS/IPO, and academic institutions, addressed the following objectives:

1) Identify critical ecological and biochemical issues related to climate change research
2) Define the role of ocean color in addressing these issues
3) Identify key ocean color parameters to be implemented as CDRs

4) Describe the procedures and infrastructure required to maintain the long term quality of ocean color products.

At a global scale, pelagic ecosystems dynamics can significantly impact the role of the ocean in the sequestration of anthropogenic greenhouse gases. At a regional scale they are critical to the management of commercial fisheries. Finally, at a local scale they serve as indicators of water quality, especially in coastal environments where human activities can strongly influence the marine environment.

Remote sensing of ocean color is the only present approach that generates consistent time series records of ecosystem dynamics at this broad range of spatial scales. As such, these records are critical for climate change research because, in order to study critical feedback mechanisms between the marine ecosystems and climate, it will be necessary to monitor and characterize how environmental perturbations propagate across these spatial scales.

In the following two sections we discuss the recommendations from the panel regarding the identification of ocean color products relevant to climate research and addressing the procedures and requirements to ensure the long-term quality and consistency of ocean color products.

II. Defining Ocean Color Products Relevant to Climate Research

Some satellite missions have been designed to monitor oceanographic parameters with a well defined geophysical interpretation, such as sea surface temperature (SST). Other missions, including sea surface height (SSH) and remote sensing reflectance in the visible portion of the electromagnetic spectrum, are not used directly to describe the marine environment. Several algorithms must be applied to the basic satellite-sensed measurements to derive ocean-relevant data products. From the spectral distribution of remote sensing reflectance, and a set of empirical and semi-analytical derived relations, we can estimate a suite of ecologically relevant properties, including algal pigment concentration (chlorophyll a), colored dissolved organic matter (CDOM), particulate inorganic and organic carbon (PIC and POC, respectively), and primary productivity. For this reason, when considering the generation of ocean color CDRs it is necessary to define first which ocean color products are relevant in addressing climate research problems and should be considered for production and archiving as Climate Data Records. Furthermore, we need to define the algorithms to be used in the derivation of these products from the satellite-measured ocean color spectrum.

The National Research Council defines two types of CDRs: fundamental (FCDRs), corresponding to calibrated and quality-controlled sensor data, and thematic CDRs (TCDRs) corresponding to geophysical variables derived from FCDRs. While the generation of FCDRs requires continuous, detailed sensor characterization and calibration, TCDRs further require the evaluation of the algorithms used to derive geophysical variables.

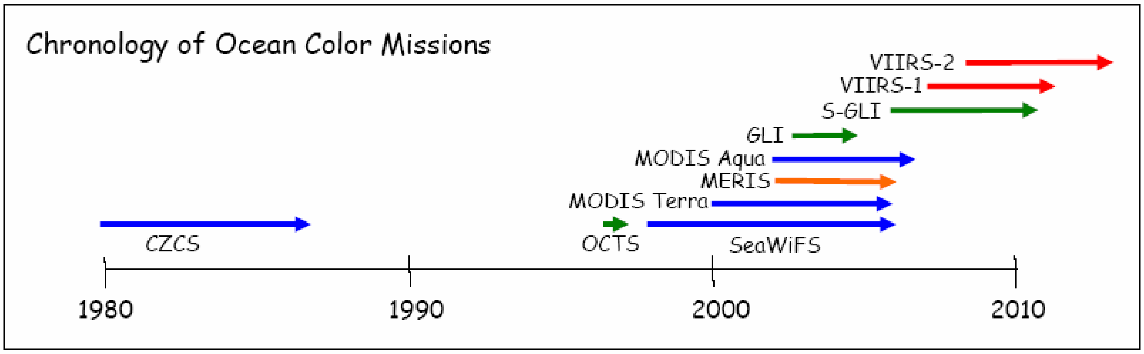
Based on this distinction, the workshop participants recommended including normalized water-leaving radiances (nLws) as an Ocean Color FCDR. In theory, nLws represent the radiances that exit the ocean through the air-sea interface with the sun at zenith (Gordon and Clark, 1981). It is from these nLws that all ecologically-relevant ocean color products are derived. The conversion from radiances reaching the sensor to nLws depends on the atmospheric correction. This correction is calculated based on ancillary remote sensing data that characterize the air-sea interface and the atmospheric content of elements that affect the propagation of light through it. Ancillary records include wind speed, air pressure, water vapor, and ozone. Hence, assuming that Level 1A data are preserved, the full sensor resolution archive of nLws as CDRs will need to include documentation that describes the algorithms used for atmospheric correction, as well as any ancillary data used in its application.

The workshop participants also recognized that there are several ocean color products derived from nLws presently available that contribute to our characterization of the spatial and temporal variability in pelagic ecosystems (e.g. chlorophyll, CDOM, POC). However, many of the approaches and algorithms used to derive these products are still evolving significantly. This is particularly the case for ocean color products derived for coastal areas. Most of the ocean color remote sensing validation effort has been associated with open ocean research. However coastal waters are optically complex and may require new approaches to calibrate, validate and refine CDR algorithms in these environments. For these reasons, many of our present ocean color products may not be considered sufficiently mature for inclusion as Thematic CDRs at this time.

However, in order to develop the procedures and ensure the infrastructure needed for the generation of ocean color TCDRs, participants recommended using chlorophyll concentration derived from nLws as a prototype TCDR. From an ocean color remote sensing perspective, chlorophyll concentration is the most mature product. It has been well-characterized and is broadly accepted by the research community as validated. Furthermore, chlorophyll concentration is a fundamental variable in pelagic ecosystem research. The approach of using chlorophyll as the initial TCDR will facilitate the future integration of other ocean color products as TCDRs which are relevant to the characterization of pelagic ecosystems and climate change. Advice and feedback from the user communities will be critical in the implementation of these new TCDRs.

III. Ensuring the Long-TermQuality and Consistency of Ocean Color Climate Data Records

The workshop discussions strongly reflected the NRC's recommendation to NOAA regarding the generation of satellite-based CDRs. This recommendation stated that: **"NOAA should base its satellite based climate data record generation program on lessons learned from previous attempts, which point out several characteristics of satellite climate data records, including the need for continuing calibration, validation, and algorithm refinements, all leading to periodic reprocessing and reanalysis to improve error quantification and reduce uncertainties".**



Starting with the Coastal Zone Color Sensor, the research community has developed extensive experience in the generation of ocean color products, the monitoring of sensor stability over the duration of a mission, and the evaluation of the consistency of products derived from sensors with different characteristics (Barnes et al. 2003; McClain et al. 2004). To secure the continuity and consistency of CDRs, it will be necessary to maintain and further develop these procedures to accurately evaluate changes in the performance of a sensor during its lifespan, potentially affecting FCDRs, the consistency across sensors, as well as potential changes in TCDR algorithms resulting from improvements in sensor technology over the course of successive satellite missions. Moreover, a rigorous and continuing program of scientific research and data analysis will be needed to ensure the quality of the CDRs. To this end the workshop participants recommended the formation of a science team to oversee the quality controls of FCDRs and the development and validation of ocean color TCDRs.

In addition, the generation of ocean color CDRs will require consistency across multiple platforms with respect to:

1) Calibration
2) Algorithms
3) Spatial and temporal resolution
4) Quantification of errors and biases
5) Data format
6) Access
7) Analysis tools

Calibration activities should cover pre-launch and periodic post-launch sensor characterization, vicarious calibration monitoring, and satellite to satellite cross-calibration. These activities are critical if we consider that instrument-specific biases, sensor degradation, and orbital drift will affect the creation of consistent CDRs. While the pre-launch calibration of a sensor is a standard procedure, we stress that a detailed sensor characterization involving the oversight from both a science and an engineering team will strongly benefit the post-launch interpretation of the data and the determination of uncertainties in the derivation of TCDRs.

On-orbit sensor calibration should include the use of cold space and the Moon as stable reference targets. The stability of the Moon’s emissivity should serve as a reference from which sensor degradation can be monitored and quantified. Lessons learned from the SeaWiFS and MODIS missions indicate that this approach to correct sensor drift is essential to provide reliable long-term trends on climate variability. However, maneuvering the spacecraft to point the sensor at the Moon or a cold space target may affect negatively orbit stability, which may be critical to other missions flying on the same platform, such as altimetry.

Orbital drift and drift in the observation time may affect significantly the consistency of the CDRs, unless the effects are monitored and characterized through periodic vicarious calibrations. Vicarious calibration of ocean color sensors through the comparison of nLws measured simultaneously by the sensor in orbit and in situ is labor intensive and expensive as a result of the high sensitivity and accuracy required to derive nLws. To date, this critical effort has been supported almost exclusively by NASA through the Marine Optical BuoY (MOBY) program led by Dennis Clark (NOAA NESDIS). To ensure the quality of ocean color CDRs, the continuation and consistency of this effort will need to be ensured. Furthermore, because this effort has focused on the characterization of the sensor in open ocean waters, NOAA will need to consider expanding this effort to optically complex waters, such as those found in coastal environments, in order to improve the use of present ocean color data in these regions.

Cross-satellite calibration will be required to adjust sensors to a common performance baseline. This adjustment is critical for long-term studies involving multiple sensors and platforms. To achieve this goal, workshop participants recommend that, for NPOESS, there should be at least 1 year overlap between satellites carrying ocean color sensors in the same orbit. One year is a minimum requirement to assess potential seasonal biases between the performances of two sensors. Although this is a critical requirement, the present NPOESS launch-to-failure strategy may preclude cross-satellite calibration. However there will be both a 0930 and a 1330 satellite carrying VIIRS, and there should be considerable overlap in time on orbit between the two. So if one can use both, perhaps in combination with MOBY, lunar imaging and other satellites there may be a basis for cross calibration. This option should be explored, although it is important to note that the 0930 VIIRS will be extremely limited in its coverage because of low solar angles in most of the swath.

In situ characterization of marine optical constituents supporting algorithm development, validation and algorithm refinement, are ongoing component of ocean color remote sensing research. Because many particulate and dissolved constituents that vary in their relative water column concentration contribute to the absorption and scattering of light, the deconvolution of their signatures from the spectral distribution of water leaving radiances remains a challenge, especially in coastal environments. In this context, NASA’s SIMBIOS program should be considered as a successful model on how to foster, coordinate, and support the involvement of the research community in algorithm development and validation efforts.

Consistency in algorithms, as well as in spatial and temporal resolution across multiple platforms is required not only to facilitate the merging of ocean color data from different platforms, but also to decrease the uncertainty associated with CDRs spanning multiple sensors (see below: “Quantification of Errors and Biases”). The consistency in algorithms ensures that detected temporal changes in a particular ocean color product reflect changes in the geophysical variable being monitored, rather than changes in its derivation. For this reason, we will need to balance the needs for algorithms that ensure consistency across platforms, even if they are somewhat less capable in their geophysical interpretation, with the expectation that future improvements in sensor design and technologies will bring a generation of new algorithms that increase the capabitilies and performance in the ocean color data sets.

The derivation of scales of heterogeneity in space and time are affected by our choice of resolution scales. since climate change can be reflected by long term changes in the observed mean as well as in the variance of a given geophysical variable, cross-satellite consistency in resolution scales ensures that changes in the calculated CDR variance spanning multiple platforms reflects real trends in environmental variability.

Although there is a perceived notion that our understanding of a system will increase with increase spatial and temporal sampling resolution, we must consider our present understanding of scales of variability in open ocean marine ecosystems that are relevant to climate change research. For these reasons, a 10 km and daily global resolution of TCDRs appears to be appropriate. However, higher spatial resolution may be needed when addressing the study of long term ecosystem trends at local levels, such as in coastal environments. In any case, Level 1 data, and ancillary fields required for the derivation of FCDRs should be archived at full sensor resolution.

Quantification of errors and biases is needed to generate CDRs with well-defined levels of uncertainty. It is the uncertainty associated with a given CDR that determines the minimum trend that can be detected with a given record. Ground-truthing a satellite-derived ocean color product is not sufficient for its validation. In addition, we require establishing uncertainty levels. This is usually done using principles of error propagation from the raw data to the final product derivation and through comparisons with independent correlative measurements. Hence, consistency in the quantification of errors and biases across platforms will be needed to facilitate the interpretation of trends observed in CDRs.

Consistency in data format and access to data records, including all ancillary data and information used in their creation (i.e. metadata), such as ocean color algorithms, calibration records and their documentation, should be standardized across platforms to facilitate easy and inexpensive access by the users. Previous experience indicates that ocean color remote sensing programs are most successful when there is an early and clear commitment by the agency to develop and maintain data stewardship, easy data access, and processing support. The SeaWiFS program is a clear example of how NASA’s commitments to support these activities through the Ocean Biology Processing Group contributed to the success of this Ocean Color mission (McClain et al., 2004).

The merging of data and the comparison of data from overlapping missions are critical activities in the generation of long term CDRs. These efforts will be greatly facilitated if data formats are consistent. This consistency will also help to develop and make available analysis tools that can be used by the community at large in the generation of CDRs at a local, regional, or global scale. In addition, because of the large volume of data expected to be created through a CDR program, it will be necessary for NOAA to ensure a data management infrastructure that allows the support of multiple data formats in order to facilitate a variety of uses, including basic research as well as socio-economic applications.

Data archive, periodic reprocessing and reanalysis are critical components in the generation and maintenance of CDRs, imposing new infrastructure and logistic requirements on NOAA. The data quality levels needed for Climate Research are significantly higher than those accepted for the generation of operational data products. For example, ocean color algorithms used to derive CDRs require co-located determinations of atmospheric ozone and water vapor content used for atmospheric correction, which are unavailable in real time. In addition, the ongoing nature of algorithm refinement and satellite calibration activities require continual reprocessing capabilities. For these reasons, NOAA will have to ensure the development and maintenance of the infrastructure required for long term archive and reprocessing of CDRs. This archive will need to include all CDR metadata, including ancillary fields and algorithm documentation, required to support both, reprocessing and reanalysis. Because one of the main goals of a long term CDR program is to provide consistent time series observations to the next generation, the access to the archived data and the metadata should provide all the information needed to recreate CDRs based on the archived Level 1 data. In addition, due to the large data volumes that CDR programs will generate, the archival structure should consider the implementation of basic features such as the capability for temporal searches and data subsetting.

IV Sharing Experience and Responsibilities

With the advent of the National Polar-orbiting Operational Environmental Satellite System (NPOESS) with the first satellite to be launched early in the next decade, NOAA is playing an increasing role in the design and implementation of remote sensing ocean color missions. However, this transition of responsibilities for ocean color CDRs from NASA to NOAA must take place considering the lessons learned from previous and ongoing ocean color missions, as well as the expertise that each one of these agencies has in the generation and validation of ocean color products. The NPOESS Preparatory Project (NPP), which is scheduled for launch later this decade, will carry the first Visible Infrared Imager Suite (VIIRS) can be a bridge between NASA's research ocean color missions and the operational missions of NPOESS. However, there is a possibility that NPP will be launched after MODIS on EOS Terra and EOS Aqua have ceased operations. This will complicate the "bridging" part of the mission from EOS to NPOESS.

NASA has a long experience in the successful design and implementation of remote sensing ocean color research missions and in the merging of datasets collected across multiple platforms. For this reason, NASA must play a major role in the implementation of an ocean color Climate Data Record program. This role should not be restricted to a transfer of knowledge and technologies. While NOAA's proven strength has been in the development and maintenance of long term operational programs like the weather satellite program, NASA's strength resides not only in the development and testing of new technologies, but also in the use of satellite products in research programs. This research aspect of ocean color remote sensing is fundamental for the understanding and interpretation of ocean color climate records and should remain as an integral part of a climate research program.

Testing, improving, and validating ocean color algorithms are ongoing efforts that require the involvement of the research community. NOAA will need to fund an extramural research program to validate ocean color products, including the reduction of uncertainties on ocean color products during the ongoing missions. In this context, NOAA's effort in supporting climate research should be inserted as part of the multi-agency U.S. Climate Change Science Program (CCSP). Because the goals and management structure of the CCSP are similar to those of NOAA's CDR program, this partnership will benefit both programs by helping the coordination between data gathering and research activities between multiple agencies, including oceanographic field and modeling efforts, such as those contemplated in the North American Carbon Program (NACP) and the Ocean Carbon and Climate Change (OCCC) program. In addition, this partnership will facilitate international collaboration in the area of climate change research.

Finally, NOAA's climate research mandate implies a long term commitment of both financial resources and manpower to make possible this endeavor. From this perspective, a close collaboration between NOAA and CCSP is required to facilitate, at both the national and international level, the leveraging of funds and personnel from other agencies, academia, and private industry that are needed to successfully support a long term climate research program.

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