International Network for Sensor Inter-comparison and Uncertainty assessment for Ocean Color Radiometry (INSITU-OCR)

Working toward consistency and accuracy in the development of essential climate variables from multiple missions

Executive Summary

The Ocean Color Radiometry - Virtual Constellation (OCR-VC) developed in the context of the Committee on Earth Observation Satellites (CEOS), aims at producing sustained data records of well calibrated and validated satellite ocean color radiometry to assess the impact of climatic changes on coastal and open sea waters. Within this framework, the *International Network for Sensor Inter-comparison and Uncertainty Assessment for Ocean Color Radiometry* (INSITU-OCR) initiative aims at integrating and rationalizing inter-agency efforts on satellite sensor inter-comparisons and uncertainty assessment for remote sensing products with particular emphasis on requirements addressing the generation of Ocean Color Essential Climate Variables (ECV) as proposed by the Global Climate Observing System (GCOS). Under the guidance of the International Ocean Color Coordinating Group (IOCCG), representatives of Space Agencies and Institutions supporting INSITU-OCR agreed on a series of recommendations on activities critical to ensure high accuracy and consistency among products from present and future ocean color missions. Those recommendations, as consolidated here, call for thoughtful consideration by Space Agencies contributing to OCR-VC in view of achieving the final goal of developing consistent long-term Climate Data Records. Key recommendations address: i. space sensor radiometric calibration, characterization and temporal stability; ii. development and assessment of satellite products; iii. *in situ* data generation and handling; iv. information management and support. Special consideration is given to traceability, application and accessibility of the necessary *in situ* measurements, which are a fundamental element of any ocean color mission.

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Introduction

This White Paper provides recommendations relevant to the production of long time-series of consistent and accurate Ocean Color Essential Climate Variables[1] (ECVs), namely Ocean Color Radiometry (OCR) and derived chlorophyll-a concentration from multi-mission satellite ocean color data, in view of creating Climate Data Records (CDR). These recommendations, mostly addressed to Space Agencies contributing to the Ocean Color Radiometer – Virtual Constellation (OCR-VC), indicate a number of critical actions related to: i. space sensor radiometric calibration, characterization and temporal stability; ii. development and assessment of satellite products; iii. *in situ* data generation and handling; iv. information management and support.

The range and complexity of activities required to thoroughly address the proposed recommendations entail an efficient coordination of inter-agency contributions. It is envisaged that INSITU-OCR should be implemented through a modular approach encompassing two complementary components: *i*. a central coordination office with the main function of facilitating communication and merging information; and *ii*. a series of dedicated working groups to actively address specific issues (e.g., space sensors calibration, protocols for *in situ* measurements, bio-optical modeling, data management). The working groups, chaired by different team members on a rotating basis, will communicate their findings to the central coordination office responsible for disseminating this information to the sponsoring agencies.

[1] Systematic Observation Rrequirements for Satellite-Based Data Products for Climate. Supplemental details to the satellite-based component of the "Implementation Plan for the Global Observing System for Climate in Support of the UNFCCC (2010 Update)" available at http://www.wmo.int/pages/prog/gcos/documents/SatelliteSupplement2011Update.pdf .

1.0 Space Sensor Radiometric Calibration, Characterization and Temporal Stability

Accurate radiometric calibration and characterization of the individual satellite sensors is the most critical component toward achieving the goal of consistent, long-term multi-mission Ocean Color ECVs. The pre-launch calibration and characterization data are essential for understanding the instrument measurement uncertainties, to correct for measurement artifacts and to have a point of reference for monitoring instrument changes on orbit. An understanding of the effects of different instruments design on the retrieved data can be gained by an examination of the calibration and characterization data. In addition, the need for monitoring changes on orbit dictates that the calibration and characterization efforts do not end at launch. It is therefore imperative that these efforts are maintained throughout the mission lifetime. Most historical and current satellite sensors provide some mechanism for monitoring on-orbit instrument degradation and all future missions should also provide similar capabilities.

- **R1.1 Comprehensive pre-launch instrument calibration/characterization**

All satellite ocean color sensors should undergo a comprehensive pre-launch characterization including, but not necessarily limited to, the determination of the instrument spectral response function, stray-light assessment and mitigation, system linearity assessment, polarization sensitivity, temperature sensitivity, optical/electronic cross-talk and radiometric stability. Two recent, independent assessments of the needs for future ocean color sensors (Yoder et al. 2011, McClain et al. 2012) detail these and other requirements that are necessary for missions capable of delivering the Ocean Color ECVs and allowing for the exploration of advanced science questions.

Recommendation

To ensure the continuation of the current time-series of Ocean Color ECVs, it is recommended that all satellite ocean color sensors undergo a comprehensive pre-launch instrument calibration and characterization traceable to SI standards.

- **R1.2 Open access to calibration and characterization data**

In order to facilitate the comparison of data collected by multiple international missions, the characterization and calibration (both pre- and post-launch) information for the related space systems should be readily available. Open access to this information will facilitate collaboration on sensor calibration, and aid in efforts to understand and minimize differences between missions.

Recommendation

Agencies should provide open access to the comprehensive pre- and post-launch instrument calibration and characterization data for all ocean color sensors.

- **R1.3 Permanent working group on satellite sensor calibration**

To facilitate collaboration between sensor calibration teams, a joint satellite calibration working group should be formed including members from all relevant ocean color sensor teams. This working group would focus on instrument calibration methods and results, cross-calibration studies, and data quality assessments, with the goal of sharing expertise and techniques to maximize the accuracy and temporal and spatial stability of OCR from each mission. Lessons learned from this effort would also provide documentation to augment current knowhow (e.g., McClain et al., 2012), to ensure that future sensor designs and calibration systems can meet OCR requirements for Ocean Color ECVs.

Recommendation

Experts from ocean color mission calibration teams should meet regularly to review calibration and characterization methodologies and results, cross-calibration studies, and address instrument issues affecting data quality.

- **R1.4 Vicarious calibration**

Current target for absolute calibration uncertainty of satellite ocean color sensors is 0.5%. This stringent value is justified by the high accuracy requirements established for utilizing satellite ocean color products in climate and operational investigations. Such a level of accuracy can be achieved with vicarious calibration: the adjustment of pre-launch calibration coefficients using top-of-atmosphere (TOA) radiance predicted from *in situ* measurements through modeling of atmospheric radiative processes. The objective of vicarious calibration is the minimization of combined uncertainties resulting from satellite absolute pre-launch calibration and from the specific models/algorithms applied for determining primary radiometric products (e.g., normalized water-leaving radiance spectra) from TOA radiance. Vicarious calibration should be performed using *in situ* radiometry ideally performed with dedicated systems (e.g., MOBY- or BOUSSOLE-like) ensuring a high degree of accuracy and with full traceability to SI standards. The vicarious calibration site should be selected in a region where variability and complexity of the atmospheric and oceanic optical properties are low, to minimize additional sources of error due to temporal and spatial sampling differences between the satellite observation and the in situ measurement. Multiple vicarious calibration sites may offer additional information and alternative sources of data, however, these sites should be equivalent in terms of measurement accuracy, traceability and observation conditions (e.g., different complexities of the atmosphere might lead to inaccurate determinations of the aerosol type and consequently to the determination of substantially different adjustment factors for the pre-launch calibration coefficients).

Recommendation

Maintain at least one long-term vicarious calibration site with SI traceable radiometry pursuing the objective of producing and delivering highly accurate measurements collected under ideal measurement condition (e.g., spatial homogeneity, known aerosol and marine optical properties) in a region representative of global ocean observations. Multiple sites are encouraged, but their equivalence in performance is fundamental. It is essential that a rigorous metrology be established at each measurement site in view of assuring measurement traceability. Because of this, inter-comparisons of each relevant component of the vicarious calibration process should be encouraged and differences thoroughly investigated. Within such a context the adoption of a commonly agreed vicarious calibration approach, supported by sharing *of processing modules, would enhance inter-mission consistency of radiometric products. Vicarious calibration should be reassessed whenever the instrument calibration or OCR retrieval algorithm is modified, and uncertainties on the derived gains should also be reported to support the determination of OCR uncertainties.*

- **R1.5 Support for calibration teams**

All sensors undergo changes on orbit. The instrument degradation is typically rapid in the early months of a mission with the rate of decay often stabilizing within the first year. However, it often requires 3-5 years from mission launch to obtain sufficient information on the rate and nature of this decay to be able to derive adequate corrections to produce ECVs of high quality. Furthermore, experience has shown that instrument calibration efforts generally increase as instruments approach end of life and degradation becomes less predictable.

Recommendation

All agencies should consider that a fundamental requirement for the OCR-VC is to maintain support for the calibration team throughout the life of the mission. As the expertise required for this effort is highly specialized, the calibration teams should be considered associated with the measurements and not to any specific mission. Such a measurement-based approach will ensure the expertise required will span multiple missions, providing a necessary continuity and transfer of knowledge.

- **R1.6 Assess and correct for instrument degradation**

One of the most difficult issues facing the development of a consistent, long-term ECV data set is the need to distinguish between instrument degradation and real geophysical change. It is imperative that all ocean color missions provide a mechanism and the expertise to access and correct instrument degradation with sufficient accuracy to ensuring that geophysical variability can be discerned from temporal variations in instrument radiometric performance. Current and historical missions have relied on lunar observations and/or measurements of the Sun through a diffuser to achieve the temporal calibration accuracy required for Ocean Color ECVs. Knowledge of uncertainty in the temporal calibration must also be established, as this is fundamental to understanding the magnitude of geophysical variability that can be discerned from the OCR measurements.

Recommendation

It is recommended that all ocean color missions should have at least one suitable system to monitor the temporal degradation and episodic changes in sensitivity of the instrument (Yoder et al. 2011, McClain et al. 2012). Additionally, Space Agencies should commit to supporting continuous assessment and correction for temporal changes in instrument radiometric performance, and to quantifying uncertainty in the temporal calibration.

2.0 Development and Assessment of Satellite Products

The generation, verification, and application of Ocean Color ECVs require that the necessary satellite data are accessible to the scientific community.

- **R2.1 Distribution of calibrated and uncalibrated data**

Calibrated top-of-atmosphere radiance is the fundamental climate data record (FCDR) produced by satellite ocean color sensors. Given that the application of sensor characterization and calibration information is not necessarily reversible, satellite mission support teams should promote the distribution of both calibrated (i.e.. Level-1B) and uncalibrated data (e.g., Level-0 or Level-1A) with the tools necessary to apply the calibration and characterization information (i.e., calibration software and look-up tables). This will facilitate the inevitable need for reprocessing mission-long data sets as techniques evolve and new insights into sensor performance arise, eliminate the need for reacquiring large volumes of source data, and enable independent verification on sensor calibration and characterization.

Recommendation

It is recommended that in addition to distribution of calibrated data (i.e., Level 1B), the Space Agencies promote the distribution of uncalibrated data (e.g., Level-0 or Level-1A) and the sharing of tools necessary to apply the calibration and characterization information.

- **R2.2 Permanent working groups on algorithm topics**

The development of consistent multi-mission OCR measurements and satellite derived products like chlorophyll-a concentration, require the application of consistent algorithms. Several working groups have been established for specific satellite products and are working toward consensus on retrieval algorithms (e.g., IOP Algorithm Workshop). A similar working group is needed to develop standards for the atmospheric correction algorithm, including standardization of aerosol models. The continuation and expansion of algorithm working groups is needed to ensure consistency and community acceptance of multi-mission Ocean Color ECVs. Working groups should also strive to provide viable approaches for quantifying uncertainties in OCR derived products.

Recommendation

It is recommended that the Space Agencies support international working groups on OCR related algorithms and associated uncertainties, to achieve consensus on the most effective and consistent approach for multi-mission satellite application.

- **R2.3 Product uncertainties**

The quantification of uncertainties in satellite OCR and related products is needed to understand the significance of differences in products derived from different missions, and the significance of differences in satellite products related to *in situ* measurements. Uncertainty information is also needed to support confidence weighting when merging multi-mission products, and for application of satellite products into climate and ecosystem models.

Recommendation
Enforce quantification of uncertainties on a pixel-by-pixel basis in satellite OCR and derived products.

- **R2.4 Regional bio-optical algorithms**

Globally applicable bio-optical algorithms are certainly a desirable solution for the generation of satellite derived products. However, the application of algorithms at global scale may lead to unpredictable uncertainties in products from optically complex waters. Thus regional algorithms may represent an efficient solution to the problem. Nevertheless, progress in regional algorithms requires: i. accessibility to comprehensive and accurate *in situ* bio-optical data from regions exhibiting different seawater optical complexities; and ii. a major effort in algorithm development, testing and combined use.

Recommendation
Programs for the development of regional bio-optical algorithms should be promoted with emphasis on the definition of uncertainties and inter-regional merging of products. When existing data sets would not suit the purpose, new field programs should also be enforced for generating the required measurements.

- **R2.5 Open access to source codes for processing algorithms**

To aid in the development of a consistent multi-mission data set, the ability to process data from all ocean color instruments through a common set of algorithms is highly desirable. The distribution of data processing software (Level-1A or Level-0 through Level-3) in the form of source code provides fundamental and indisputable documentation on the processing algorithms and implementation details, which educates and informs the research user, facilitates collaboration on algorithm development, supports independent software verification, and generally enhances the knowledge and confidence of the end user in the OCR and derived products.

Recommendation
It is recommended that the Space Agencies offer the ability to process the data from their respective missions through a common set of algorithms and to make the source code for those algorithms open and available for review and implementation by others.

- **R2.6 Long-term field measurement programs**

By acknowledging the non-interchangeability of vicarious calibration data with validation data, accurate measurements of atmospheric and marine bio-optical properties from a variety of bio-optical regions are fundamental throughout the life of any mission to investigate the accuracy of derived products. Fully recognizing that in such a context any single measurement is certainly relevant, it is however expected that data from multiple sources are affected by different uncertainties resulting from the application of different measurement systems, calibration schemes and measurement methods.

Recommendation

Long-term measurement programs should be established and maintained beyond any individual mission relying on consolidated instruments, calibration methods and measurement protocols. In situ data designated to support satellite ocean color validation programs should be globally and seasonally distributed, and cover a broad range of water types including areas exhibiting different trophic levels as well as waters dominated by colored dissolved organic matter or sediments.

- **R2.7 Validation protocols**

Satellite product validation results from different missions are often difficult to compare because of differences in methodologies, statistical parameters and quality assurance criteria.

Recommendation

The definition, implementation and application of common validation protocols should be strongly encouraged. This should translate into the construction of matchups using identical criteria as well as reporting results through identical statistical measures.

- **R2.8 Level-3 data products generation**

Given the volume of data produced by ocean color missions, the useful application of ECVs is hindered if the data sets are only provided at the native sensor resolution and coordinate frame. The availability of global, binned data products is necessary to support climate and modeling studies, and to facilitate mission inter-comparison as well as multi-mission data merging activities (Antoine et al. 2004).

Recommendation

It is recommended that Space Agencies produce data sets of global, binned (Level-3) OCR and derived products. The binning strategy and spatial/temporal resolution of these Level-3 ECV data sets should be identical, including the use of a unified naming convention.

- **R2.9 Ancillary data**

The nature of the atmospheric correction algorithms employed to retrieve meaningful geophysical values from space-based ocean color radiometers necessitates the use of a variety of ancillary data sources ranging from meteorological data, total columnar ozone concentration, and various absorbing gases (e.g., Ozone, NO2, water-vapor). The choice of these data sources can have an impact on the retrieved variables.

Recommendation

It is recommended that the Space Agencies agree on the use of a consistent set of ancillary data sources for the production of ECVs from ocean color sensors. In case of differences, the evaluation of their effects in satellite products is highly encouraged. Finally, ancillary data should be provided in specific files independent from satellite data. This latter aspect is relevant to minimize the volume of data to re-distribute in case of any change affecting ancillary data

3.0 *In Situ* Data

Ground truth measurements are essential to any ocean color program during the successive phases of the mission. *In situ* measurements collected at times close to the satellite overpass are fundamental for: i. vicarious calibration of the satellite OCR; ii. continuous assessment of OCR quality (i.e., validation of normalized water-leaving radiance or the equivalent remote sensing reflectance); iii. validation of derived satellite ocean color products (e.g., chlorophyll-a concentration); iv. and development and verification of the bio-optical algorithms required for generating derived products (independent of any specific satellite mission).
This central position of *in situ* data necessarily calls for actions assuring their quality, preservation and accessibility.

- ***R3.1 Improving traceability of in situ measurements***

Traceability defines the capability of relating measurements to a reference. In practice, traceability is challenged by the use of different instruments, calibration standards, measurement protocols, processing codes, and quality assurance criteria. Effects of these differences may lead to unpredictable uncertainties seriously affecting applications relying on *in situ* data from merged sources.

Recommendation

Funding agencies should enforce common calibration schemes and measurement protocols, and unifying processing schemes and quality assurance criteria to ensure consistency and traceability of in situ measurements to SI standards. Inter-comparison exercises should be considered as the means to enforce traceability by promoting state-of-art on instrument calibration, measurement methods, data processing, and quality assurance. Practical implementation of inter-comparisons may entail a series of round-robins on specific topics together with training opportunities.

- **R3.2 Continuous consolidation and update of measurement protocols**

Community consensus on protocols for instrument calibration, field measurements, data analysis, uncertainty assessment and quality assurance must be established and maintained for field activities and *in situ* data handling. This requires an extraordinary effort for: i. updating current protocols, and ii. assuring the needed flexibility to quickly evaluate and incorporate new elements resulting from advances in theory, technology or practice.

Recommendation

Measurement protocols should be consolidated as a result of a critical review and update of those currently documented in peer-review literature or already included in compilations produced by former programs. Consolidated protocols should then be published using modern communication methods. A possibility would be to create "living documents" (e.g. Wiki format, easily accessible and modifiable through continuous community contributions and discussions, but envisaging mechanisms for tracking successive versions). This objective could be initiated through independent and well focused workshops on protocols for the determination of in situ data from: i. water apparent optical properties; ii. water inherent optical properties; iii. water *pigments; and iv. atmospheric optical properties. Expertise on standardization quality assurance should be represented in each leading activity.*

- **R3.3 Uncertainty budgets**

Good practice would suggest that uncertainty budgets are always quantified for measurements. In general terms, *in situ* measurements for which uncertainties are not defined cannot be considered SI traceable. The lack of this pre-requisite does not allow for a quantitative evaluation of results from the application of *in situ* measurements to vicarious calibration of space sensors, validation of radiometric or derived products, and implementation of bio-optical algorithms. Additionally, the lack of a trustworthy uncertainty estimates makes it difficult to determine the range of potential applications of *in situ* data.

Recommendation

In situ data should be linked to uncertainty budgets determined in agreement with defined protocols and accounting for a comprehensive range of uncertainty sources. Ideally these uncertainty budgets should include contributions from calibration, processing, deployment restrictions, and environmental conditions.

- **R3.4 Quality Assurance of *in situ* data**

Lack of quality assurance of *in situ* measurements might lead to the archival and successive use of data affected by artifacts (e.g., spectral inconsistencies, biases, unrealistic values).

Recommendation

Define and implement quality assurance schemes for in situ data. These criteria should be specific for the different quantities and should take benefit of ancillary information provided with the data itself (e.g., cloud cover or sea state in the case of radiometric data), empirical thresholds, closure between inherent and apparent optical properties, models estimate.

- **R3.5 Archival of *in situ* data**

Repositories for *in situ* data, hopefully specialized for vicarious calibration, validation and bio-optical modeling applications, are fundamental to support multiple satellite ocean color missions. Without secure archival of *in situ* data into long-term repositories, access or even longevity to data beyond the life of individual missions or specific measurement programs cannot be assured. Reasons for failure in permanently securing *in situ* data are generally due to lack of firm submission requirements, difficulty in envisaging benefits from data submission, or simply shortage of resources.

Recommendation

Centralized open access data repositories should be established, supported and maintained beyond any individual mission's life. Repositories should ideally have the capability of indexing data as a function of their fitness for specific applications (e.g., vicarious calibration, bio-optical modeling, and validation). Suitable mechanisms should be put in place to warrant data submission (e.g., requesting timely data delivery for field data produced within the framework of measurement programs *funded by Space Agencies, or creating benefits like full processing and quality assurance of submitted data, or, where appropriate, convincingly recommending authors exploiting archived data to contact contributors and offer co-authorship).*

- **R3.6 Community processor for *in situ* data**

The application of different processing codes is an element limiting standardization of *in situ* reference data. In fact, the use of different processing schemes and quality assurance criteria may significantly increase difficulties in tracing uncertainties, and also limit the systematic data reprocessing often required by advances in instruments characterization or protocols development.

Recommendation

Design, implement and apply community consensus processors for in situ data. This development should proceed through incremental steps, for instance by initially creating open access libraries and requesting manufacturers to adopt common (or user definable) data formats.

- **R3.7 Priority for variables to be collected**

An incomplete set of field variables may significantly reduce the effective applicability of the *in situ* data. In fact, while any *in situ* variable can be in principle relevant to support satellite ocean color missions, some variables are fundamental and their collection should be prioritized.

Recommendation

A list of variables considered essential for satellite ocean color applications should be defined and considered with high priority by any field program.

- **R3.8 General coordination of field campaigns**

Notably, oceanographic activities require extensive planning and are quite demanding in terms of infrastructure, personnel and equipment. Often, lack of information prevents exploitation of opportunities which may ensure a better use of available resources (e.g., access to instrumentation or expertise through collaborations, or simply chance for training of young scientists).

Recommendation

Establish a coordination mechanism to allow for a continuous exchange of information on forthcoming field activities to create opportunities for collaboration including instrument exchange, field training, inter-comparisons. The coordination should be instrumental in ensuring the collection of prioritized in situ variables meeting the basic needs for satellite ocean color applications. A web page service may efficiently support the activity.

4.0 Information Management and Support

A comprehensive approach to information management of the essential elements of ocean color data is critical to ensure the data, tools and associated documentation are readily available to the scientific community. Such an approach should provide access to: i. the satellite data; ii. the necessary tools to process and visualize these data; and iii. all of the pertinent documentation required to support research and applications.

- **R4.1 Accessibility and distribution of large volumes of data**

As mission data records grow, and as new and more advanced instruments are launched with increased spectral, spatial and temporal resolution, the volume of data produced increases together with the effort required for distribution. The value of these data assets to climate research continues long after missions have reached end of life. Space Agencies should ensure that investments and efforts spent to design, develop, launch, and operate an ocean color mission are protected through long-term data stewardship strategies, and that the value of these assets is fully realized by putting in place efficient systems for distributing data, free of charge, to the scientific community and to other Agencies. This may include the creation of mirror distribution sites to both improve user access and act as off-site backup mechanisms reducing the risk of data loss.

Recommendation

It is recommended that the entire archive of satellite data products be freely and easily accessible in a timely manner, and that the Space Agencies should enter into data sharing agreements so that the source data for all missions are provided to their partner Agencies as a means of facilitating inter-mission comparisons, to provide mirror sites for improved user access to the data and to act as a data-loss risk reduction mechanism. The access to data should also include the additional capability of fast extraction and prompt delivery of data products for local areas.

- **R4.2 Processing capabilities for calibration and validation activities**

Dedicated and efficient processing capabilities are essential for the production and distribution of Ocean Color ECVs. In addition to the need of supporting operational processing and regular re-processing, system architectures and computer infrastructures should be also scoped to support large-scale calibration and validation analyses (e.g., to determine vicarious calibration adjustment factors, systematically evaluate temporal and spatial stability of the space instrument, assess the accuracy of derived products and their consistency with respect to those from other historical or contemporaneous missions, or to enforce cross-calibration analyses). These often iterative development and evaluation analyses, require efficient processing architectures and infrastructures scaled to process a significant percent of the global mission data from Level-1A (or Level-0) to Level-3 in one calendar day. Thus, system throughput must grow as the mission data record expands.

Recommendation

Establish appropriately scaled processing system architectures and computer infrastructures to support substantial reprocessing for calibration and validation *analyses, in addition to operational processing and regular re-processing. It is recommended that the processing system should be able to support reprocessing for calibration and validation studies efficiently from Level-1A (or Level-0) to Level-3 at a rate of at least 5-15% of the global mission per calendar day.*

- **R4.3 Accessibility to documentation**

Documentation is fundamental to understanding of the differences between Ocean Color ECV retrievals from disparate instruments. The need for documentation starts with the instrument design and pre-launch characterization and calibration procedures, and continues through processing methods, algorithms, and data formats. Access to documentation should be a priority for any mission.

Recommendation

A minimum set of documentation on missions/data products should be made available. This should include documentation on the implementation of the instrument characterization and calibration and associated pre- and post-launch data, the relative spectral response functions for the instrument bands, and the derivation and validation of Ocean Color ECV algorithms. These may be best implemented as on-line living documents (e.g., Wiki).

- **R4.4 Data formats**

One of the challenges to working with data from different missions is the range of data formats in which these data are provided. The formats in use by current missions include HDF-4, HDF-5, HDF-EOS (ver. 4 & 5), netCDF and even proprietary binary formats. Much of the difficulties can be minimized with the use of a common data format. The netCDF format has evolved into a feature rich data format gaining in popularity within the earth observing scientific community. There are even standards developed for netCDF metadata that greatly simplify the interoperability of the format (Eaton et al., 2011). This format also has the benefit of being backward compatible with previous versions, so future versions of the format will retain the ability to recognize data sets written under previous versions.

Recommendation

It is recommended that a common data format be agreed upon for the storage of the satellite data produced by all Space Agencies. A good example is netCDF with CF compliant metadata. At a minimum, tools should be provided by the Space Agencies to allow users the ability to easily read the files – whatever the format.

- **R4.5 Support for open source data processing and visualization**

The development and maintenance of software packages for data processing and visualization should be viewed as an integral part of the mission. Current examples of such software packages include: SeaDAS – maintained and distributed by NASA; BEAM – maintained and distributed by Brockmann Consult under contract with ESA; ODESA – maintained and distributed by ACRI-ST under contract with ESA. GIOVANNI is and additional example of software that allows for data visualization and analysis. This online tool maintained by NASA overcomes the need for transferring large volumes of data and provides support to users lacking of computer power.

Recommendation
Space Agencies should support the development and distribution of open-source data processing and visualization software, including the source code used in the generation of mission Ocean Color ECVs. Additional software tools allowing for remote access and analysis of OCR and derived products are also encouraged. This effort should be considered an essential contribution to ocean color science that transcends any mission lifetime.

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