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Unique Data Repository Facilitates Ocean Color Satellite Validation

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The oceans play a critical role in the Earth's climate, but unfortunately, the extent of this role is only partially understood. One major obstacle is the difficulty associated with making high-quality, globally distributed observations, a feat that is nearly impossible using only ships and other ocean-based platforms. The data collected by satellite-borne ocean color instruments, however, provide environmental scientists a synoptic look at the productivity and variability of the Earth's oceans and atmosphere, respectively, on high-resolution temporal and spatial scales.

Three such instruments, the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) onboard ORBIMAGE's OrbView-2 satellite, and two Moderate Resolution Imaging Spectroradiometers (MODIS) onboard the National Aeronautic and Space Administration's (NASA) Terra and Aqua satellites, have been in continuous operation since September 1997, February 2000, and June 2002, respectively. To facilitate the assembly of a suitably accurate data set for climate research, members of the NASA Sensor Intercomparison and Merger for Biological and Interdisciplinary Oceanic Studies (SIMBIOS) Project and SeaWiFS Project Offices devote significant attention to the calibration and validation of these and other ocean color instruments. This article briefly presents results from the SIMBIOS and SeaWiFS Project Office's (SSPO) satellite ocean color validation activities and describes the SeaWiFS Bio-optical Archive and Storage System (SeaBASS), a state-of-the-art system for archiving, cataloging, and distributing the in situ data used in these activities.

Ocean color instruments typically measure the upwelling spectral radiant flux emanating from the top of the Earth's atmosphere at discrete visible and near-infrared wavelengths. Atmospheric correction algorithms are applied to these data to remove the contribution of the atmosphere from the signal and to produce estimates of the spectral radiant flux at the sea surface. The resulting water-leaving radiance, $L_{wn}(\lambda)$, may in turn be used to estimate a number of geophysical data parameters, such as the concentration of chlorophyll *a*—the phytoplankton pigment—via the application of additional bio-optical algorithms.

Researchers use the radiances and derived parameters, chlorophyll *a* in particular, to monitor temporal changes in the marine ecosystem, and to investigate the role of oceanic photosynthesis and net primary productivity in the Earth's carbon budget [*Behrenfeld et al.*, 2001]. A secondary product of the atmospheric correction algorithm is the determination of aerosol optical thickness (AOT) at 865 nm, $\tau_a(865)$, a measure of aerosol column concentration. These data are incorporated into studies of aerosol radiative forcing, cloud formation, and climate response [*King et al.*, 1999]. The spatial scale of each discrete observation, or pixel, of SeaWiFS and MODIS Terra and Aqua is approximately 1 km^2 when viewing the Earth at nadir. The three sensors observe an average of 15% of the ocean each day, and up to 50% over 4 days, after accounting for the effects of cloud coverage and contamination by excessive Sun glint. The percentages rise to 25% and 65%, respectively, if data from the

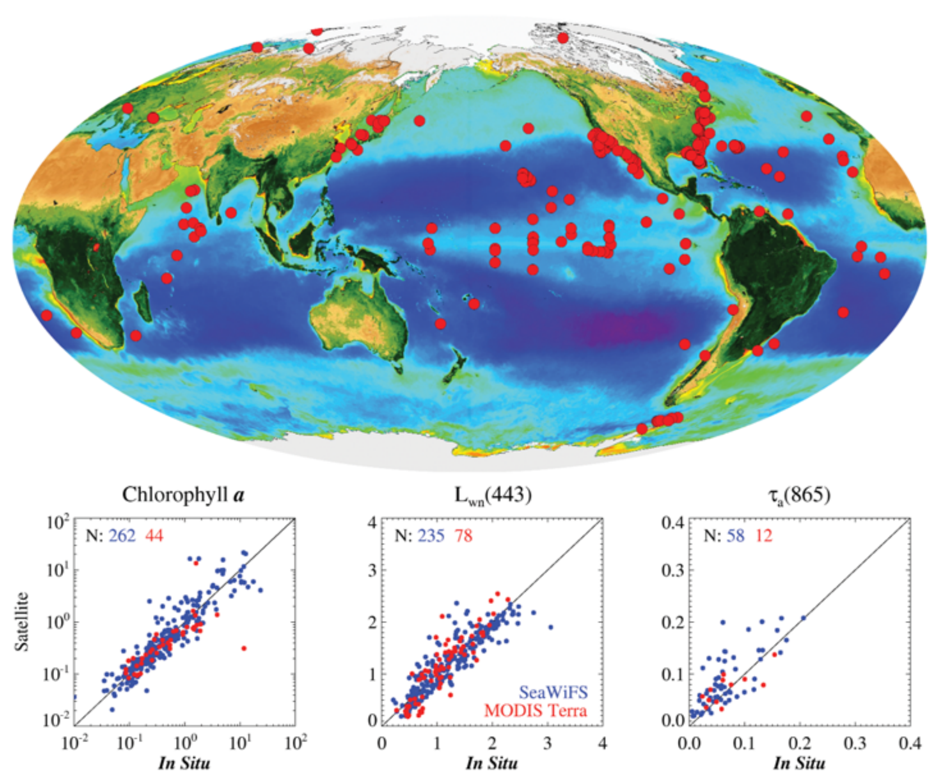

Fig. 1. The global distribution of valid data points included in the SSPO's SeaWiFS and MODIS Terra validation activities, as of February 2003, overlaying the SeaWiFS biosphere (top panel). Scatter plots of coincident in situ and SeaWiFS (blue) and MODIS Terra (red) observations for chlorophyll a *(mg m^{-3}), normalized water-leaving radiance at 443 nm (μW cm^{-2} nm^{-1} sr^{-1}), and aerosol optical thickness at 865 nm (unit-less) (from left to right in the bottom panel). The chlorophyll* a *data are displayed in a log-log scale because of their log-normal distribution. A one-to-one line has been included for clarity. For SeaWiFS, data from the fourth re-processing (July 2002) were used and all available data were considered. For MODIS, data from Terra Collection 4 were used and only data from the ocean color validated period were considered (1 November 2000 through 19 March 2002).*

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three instruments are merged [*Gregg et al*,. 1998]. At such spatial and temporal scales, these data provide the scientific community a high-resolution means of studying the atmosphere and marine biosphere.

The SSPO adopted direct comparison with in situ measurements as its principal means of satellite data product validation, where typically, the average value of several satellite pixels is compared with a single, discrete field measurement. As of this writing, radiometric profiles, chlorophyll *a* concentrations, and discrete AOT measurements from a globally distributed data set were available for comparison with satellite data products (Figure 1, Table 1). MODIS Terra was included in Figure 1 to demonstrate that the routines employed by the SSPO are satellite-independent and not specific to SeaWiFS. In fact, the SSPO regularly applies these data and methods to other U.S. and international satellite-borne ocean color missions, when the satellite data products are accessible. The MODIS Oceans Team plans on re-processing the Terra ocean color data in the near future and, as such, statistics generated from these precursory data are not included in Table 1.

Briefly, the results for SeaWiFS indicate (1) reasonably conformity for $L_{wn}(443)$, with a median absolute percent difference less than 14% and slope statistically equal to 1.0; (2) slightly higher variance for chlorophyll *a*, particularly at the highest concentrations, with a slope equal to 1.0; and (3) moderate agreement for $\tau_a(865)$, with an overall slight positive bias and limited observations with values above 0.1. Note, however, that the number of coincident observations for $\tau_a(865)$ is small for this analysis. Similar analyses are performed for additional data products, including all water-leaving radiances, but are not included for the sake of brevity. $L_{wn}(443)$ was highlighted in this analysis because it is a common data product for many instruments, and because of its fundamental role in algorithms used to estimate chlorophyll *a* concentrations. Albeit a derived product, chlorophyll *a* was treated independently because of its customary role in marine ecosystem monitoring.

Table 1. Median absolute percent difference of coincident SeaWiFS and in situ observations, and the slope (with standard error), coefficient of determination (r^2), and root mean square error (RMSE; the root of the residual mean square, in units equal to that of the observation), derived from reduced-major-axis regression analysis of the coincident observations. The chlorophyll *a* data were transformed prior to the regression analysis to account for their log-normal distribution. An asterisk (*) indicates the slope and intercept are statistically equal to 1.0 and 0.0, respectively, via a student's *t* analysis at $\alpha = 0.05$.

	N	% Difference	Slope (± SE)	r^2	RMSE
Chl *a*	262	27.3	1.034 (0.025)*	0.849	0.567
$L_{wn}(443)$	235	13.2	0.977 (0.031)*	0.786	0.257
$\tau_a(865)$	58	34.8	1.136 (0.108)	0.555	0.038

Compilation of an In Situ Data Set

The validity of the above analyses relies on the use of exceptional ground-truth data. As such, high-quality, globally distributed in situ measurements are a prerequisite for satellite data product validation and algorithm development. The SeaWiFS Project, for example, is tasked with producing normalized water-leaving radiances with an absolute accuracy of 5%, a goal that requires in situ radiometric measurements with an accuracy finer than 5% [*McClain et al.*, 1992]. Unfortunately, the volume of in situ data suitable for such activities has historically been limited because of paucity of comprehensive, simultaneous observations and the many difficulties associated with worldwide sampling. Because of their required accuracy, these data are additionally limited by varying measurements and data processing techniques. In contrast, most current ocean color missions, including SeaWiFS and MODIS Terra and Aqua, provide a synoptic view of the Earth every few days. The use of temporally and geographically limited field data in support of such missions introduces bias into validation analyses and algorithm development, and often precludes time series and data merger analyses.

The SSPO addressed these issues, in part, by initiating the development of SeaBASS, a system designed to archive, catalogue, evaluate, and distribute in situ oceanographic and atmospheric data [*Hooker et al.*, 1994, *Werdell and Bailey*, 2002]. SeaBASS was originally populated with radiometric and phytoplankton pigment data used in the SeaWiFS Project's validation and algorithm development activities. To facilitate the assembly of a global data set, SeaBASS currently includes data collected by the SIMBIOS Program, as part of NASA's SIMBIOS Research Announcements (NRA) released in 1996 and 1999, which has aided considerably in minimizing spatial bias and maximizing data acquisition rates [*Fargion and McClain*, 2003]. To develop consistency across multiple data contributors and institutions, the SSPO also defined and documented a series of in situ data requirements and sampling strategies that, when followed, assure that any particular set of measurements are acceptable for algorithm development and ocean color sensor validation [*Mueller et al.*, 2002a and 2002b].

Currently, the SeaBASS bio-optical data set includes measurements of marine optical properties, phytoplankton pigment concentrations, and other related oceanographic and atmospheric data, such as water temperature, salinity, and AOT. Data are collected using a number of instrument packages from a variety of manufacturers, such as profilers and hand-held instruments, on a variety of platforms, including ships and moorings. As of February 2003, SeaBASS includes data collected by research groups at 44 institutions in 14 countries, encompassing over 1,100 individual field campaigns. These data include over 225,000 phytoplankton pigment concentrations, 11,000 continuous depth profiles, 15,000 spectrophotometric scans, and 15,000 discrete measurements of AOT. Participants of the SIMBIOS Program contributed just over 87% of these data. Other NASA-funded researchers and many U.S. and international voluntary contributors provided the remainder.

Data collected under funding from NASA's SIMBIOS and Ocean Biogeochemistry Programs must be submitted to SeaBASS within 6 months and 1 year, respectively, of their collection. To expedite the compilation of these high-quality data, the SSPO makes use of a rigorous series of submission protocols and quality-control metrics that range from file format verification, to inspection of the geophysical data values. This ensures that observations fall within expected ranges and do not clearly exhibit characteristics of measurement problems. As an example, radiometric data values are qualitatively compared with theoretical maxima, estimated using several well-validated, bio-optical algorithms, and spectra are evaluated via band ratios and spectral normalization. Furthermore, the SSPO maintains a pool of regularly calibrated Sun photometers, whose data are processed internally using customized routines and ancillary data to ensure the best possible consistency and to minimize uncertainty [*Fargion et al.*, 2001].

The Validation Paradigm

Once the in situ data are available, validation of satellite data products requires two steps: (1) reduction of the ground-truth data to relevant observations, and (2) preparation of the coincident satellite imagery. The in situ data are first screened to eliminate redundant observations at a given site, then further reduced to temporally-relevant observations, defined by the SSPO as data collected within a 3-hour window of an available satellite overpass, but no earlier than 9 A.M. or later than 3 P.M. local time to ensure adequate solar illumination. A box of coincident satellite pixels is defined, centered on the in situ measurement, and invalid pixels, flagged by the satellite atmospheric correction and bio-optical algorithms, are discarded. If more than half of the non-land pixels remain and their relative variability is within a predefined statistical threshold, the median of the valid pixels is calculated and considered suitable for comparison with the coincident in situ observation.

The retrieval of meaningful results from the validation activity, however, relies on recognition of the assumptions made when comparing the two dissimilar observations. For example, careful consideration must be made of the disparate spatial scales, biased geographic distribution, and temporal differences of the observations. Drawing on experience achieved through statistical and iterative analyses, the SSPO employs validation methods that both account for, and reduce error introduced by, these dissimilarities whenever possible [*McClain et al.*, 2000]. As an example, rather than compare a single satellite pixel with a coincident in situ observation, sensitivity studies suggest the that use of a 5 x 5 pixel box adds confidence to the satellite retrieval while limiting inaccuracy posed by geophysical variability at the observation site and navigation, sensor, and algorithm errors in the satellite observations [*Hu et al.*, 2001].

The routines developed by the SSPO are satellite-independent and are currently used to operationally validate both SeaWiFS and MODIS Terra level-2 data products. Although not addressed specifically in this article, comparable analyses are executed regularly for other U.S. and international satellite-borne ocean color instruments. The data included in Figure 1 and Table 1 are valid as of February 2003. These results are updated regularly and posted publicly online as new validation data are acquired and submitted to SeaBASS.

Data Availability

The SeaBASS Web site (http://seabass.gsfc.nasa.gov) provides a complete description of the system architecture, comprehensive documentation on policies and protocols, and direct access to the bio-optical data set and validation results. Briefly, the architecture of SeaBASS consists of three tiers: (1) geophysical data and metadata recorded in digital text files that adhere to ASCII format; (2) a directory tree structure residing on a dedicated server at the NASA Goddard Space Flight Center for storage of the data files; and (3) a relational database management system (RDBMS), built using the SQL Server product from Sybase, Inc., used to catalog and distribute the data and files. Through the use of online search engines that interface with the RDBMS, the full bio-optical data set is queriable and available to authorized users via the Internet. The impetus for this design was easy data access, including online access, with sufficient security to limit usage when necessary, all while accommodating a variety of computer operating systems. In addition, SeaBASS was built to be expandable and flexible enough to accommodate large data sets and multiple data types.

All data collected prior to 31 December 1999 are fully available to the general public. To protect the publication rights of contributors, access to more recent data is limited to SIMBIOS Science Team members (current NRA), NASA-funded researchers, and regular voluntary contributors, as defined by the current SeaBASS access policy. Other investigators are able to query for generic information about these restricted data, but will be referred to the contributors for access to the data itself. Upon the conclusion of each SIMBIOS NRA, restricted data collected under that NRA are made publicly available. These public data are also released to the National Oceanic and Atmospheric Administration's (NOAA) National Oceanographic Data Center (NODC) for inclusion in their archive.

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Abandoned Mines, Mountain Sports, and Climate Variability: Implications for the Colorado Tourism Economy

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Until recently, the allure of the mountains in the American West was primarily extractive, for commodities like timber, water, and precious metals [*Baron et. al.*, 2000]. Now, the effective marketing and management of the region's "white gold" by the ski industry has stimulated significant recreation-related growth and development in the last several decades. Under an uncertain climatic future, however, these burgeoning industries, and the communities that have grown up in relation to them, are facing water quality constraints inherited from historical mining practices, causing mountain water to become a limited resource more valuable than the precious metals of the past. Further, the current lack of proven, in-situ approaches for addressing distributed, mining waste pollution of fresh water complicates potential remediation efforts.

In addition, the recent severe drought in Colorado has highlighted the importance of high mountain water sources to economic wellbeing in the Western United States. When coupled with rapidly growing mountain development and the environmental legacies of historical hard rock mining, fears of insufficient quantities of precipitation have renewed

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