The continuity of ocean color measurements from SeaWiFS to MODIS

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ABSTRACT

The Ocean Biology Processing Group (OBPG) at NASA's Goddard Space Flight Center is responsible for the processing and validation of oceanic optical property retrievals from the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) and the Moderate Resolution Imaging Spectroradiometer (MODIS). A major goal of this activity is the production of a continuous ocean color time-series spanning the mission life of these sensors from September 1997 to the present time. This paper presents an overview of the calibration and validation strategy employed to optimize and verify sensor performance for retrieval of upwelling radiances just above the sea surface. Substantial focus is given to the comparison of results over the common mission lifespan of SeaWiFS and the MODIS flying on the Aqua platform, covering the period from July 2002 through December 2004. It will be shown that, through consistent application of calibration and processing methodologies, a continuous ocean color time-series can be produced from two different spaceborne sensors.

Keywords: MODIS, SeaWiFS, ocean color, calibration, validation, data processing.

1. INTRODUCTION

Ocean color sensors are designed to retrieve the spectral distribution of upwelling radiance just above the sea surface, which is referred to as the water-leaving radiance or Lw(λ). The water-leaving radiance can be used to estimate a number of geophysical data parameters, such as the concentration of chlorophyll *a*, via the application of additional bio-optical algorithms (e.g., O'Reilly 1998). The Coastal Zone Color Scanner (CZCS), launched onboard the National Aeronautics and Space Administration (NASA) Nimbus-7 spacecraft, provided the first ocean color data set derived from a spaceborne sensor (Hovis 1980), and subsequently the first global view of the distribution of chlorophyll *a* (Feldman 1989). The success of CZCS prompted NASA to launch additional ocean color capable sensors into low earth orbit, including the Sea-viewing Wide Field-of-view Sensor (SeaWiFS, McClain 1998), and two Moderate Resolution Imaging Spectroradiometers (MODIS, Esaias 1998).

The SeaWiFS is a multi-spectral radiometer that has been in a sun-synchronous, 12:00 p.m. orbit since August 1997. SeaWiFS views the earth in eight spectral bands covering the visible and near-infrared (NIR) range from 400-900 nm. The MODIS instrument is currently flying on both the Aqua and Terra platforms of the Earth Observing System (EOS). The Terra platform was launched in December 1999 into a sun-synchronous 10:30 a.m. orbit, and the MODIS instrument on Terra (MODIS-Terra) has been in continuous operation since February 2000. The Aqua platform was launched in May 2002 into a sun-synchronous 1:30 p.m. orbit, and MODIS-Aqua has been in continuous operation since June 2002. The MODIS sensors measure radiance in 36 spectral channels covering the range from 400 nm to 14.4 μm, to support land, ocean, and atmospheric measurements. The bands of primary interest to ocean color applications are the 9 channels covering the spectral range from 400-900 nm. Both SeaWiFS and MODIS are scanning radiometers, collecting data over a wide swath with a pixel resolution of approximately 1-km x 1-km at the minimum view angle. The mission design allows for global observation of the top-of-atmosphere (TOA) radiance every two days. Unlike MODIS, the SeaWiFS mission was designed specifically for ocean color measurements, so it has some advantages such as the ability to tilt the optics to avoid specular reflection of the Sun on the ocean surface (glint).

The process of retrieving water-leaving radiance from measured radiance at the TOA requires a well-calibrated instrument and a processing algorithm for both removal of the atmospheric signal and normalization for solar illumination and viewing geometry effects. Prior to 2004, the ocean color products derived from the SeaWiFS and MODIS sensors were processed using the calibration methodologies and software developed by the respective instrument teams. In early 2004, NASA designated responsibility for all ocean color processing and related calibration and validation to the newly formed Ocean Biology Processing Group (OBPG). As part of a NASA initiative known as "Missions to Measurements," the idea was to consolidate ocean color processing, calibration, validation, and distribution within a single measurement team, to reduce cost and enhance the quality and consistency between ocean color mission products.

The OBPG was formed from the existing SeaWiFS and SIMBIOS (Fargion 2003) groups. The immediate task, therefore, was to integrate MODIS ocean color processing and validation into the existing SeaWiFS framework. Due to well-documented instabilities in the MODIS-Terra instrument (e.g., Erives 2004), the OBPG and NASA Headquarters decided to concentrate initial efforts on the MODIS-Aqua ocean color products. This paper describes the integration approach and provides some details on the calibration and algorithm changes implemented into the multi-sensor processing environment to achieve a consistent ocean color time-series spanning the operational lifetime of the two instruments. This is followed by an analysis of the retrieved water-leaving radiances, including comparison to field measurements and evaluation of the global time-series.

2. SPECTRAL DIFFERENCES

Table 1 presents a list of the spectral channels of MODIS and SeaWiFS that are used in the retrieval of $Lw(\lambda)$. By assuming that the ocean is totally absorbing in the NIR, the observed radiances in MODIS bands 15 and 16 or SeaWiFS bands 7 and 8 are used in conjunction with pre-computed tables to estimate the atmospheric component of the observed radiance (Gordon & Wang 1994). The red band near 670 nm can be used to derive a correction for residual NIR radiance exiting the ocean (Stump 2003). The goal is to remove the atmospheric signal from the observed radiance in the 400-600 nm regime and retrieve the water-leaving radiance in these visible wavelengths. The $Lw(\lambda)$ is then normalized to remove effects of solar illumination and viewing geometry, and atmospheric attenuation losses (e.g., Gordon & Clark 1980). The atmospheric correction process accounts for the full relative spectral response of the instrument in each channel, including out-of-band response (Gordon 1995). This normalized water-leaving radiance, $nLw(\lambda)$, is then adjusted from full-band spectral response to a nominal 10-nm square band-pass (Wang 2000, Wang 2001, Franz 2003) centered on the wavelengths listed in Table 1.

MODIS Band	SeaWiFS Band	MODIS Wavelength	SeaWiFS Wavelength
8	1	412	412
9	2	443	443
10	3	488	490
11	4	531	510
12	5	551	555
13	6	667	670
15	7	748	765
16	8	869	865

Table 1: MODIS and SeaWiFS spectral bands used in ocean color processing.

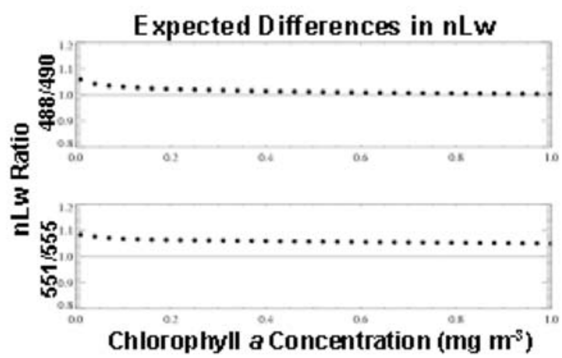

Figure 1: Effect of band center wavelength differences on water-leaving radiances at various chlorophyll concentrations.

In principal, variations in the magnitude and relative spectral distribution of $nLw(\lambda)$ is driven by changes in the concentration of biological and detrital matter suspended or dissolved in the water body, including phytoplankton pigments, non-algal particulate matter, and dissolved organic carbon. In open ocean locations, where the concentrations of such sources is low and slowly-varying, the nLw(λ) retrieved at equivalent MODIS and SeaWiFS wavelengths should be very similar, assuming the atmospheric correction of the observed radiance perfectly accounts for varied meteorological and atmospheric conditions and diverse viewing and solar geometry. Furthermore, in such open ocean conditions, expected differences in nLw(λ) due to small discrepancies in band center wavelengths can be reasonably well predicted using a bio-optical model. The model of Morel & Maritorena (2001) was used to produce Figure 1, which shows the expected differences between the 488 and 490-nm channels and the 551 and 555-nm channels as a function of chlorophyll *a* concentration, the dominant pigment in most open ocean cases. The SeaWiFS channel at 510 nm and the MODIS channel at 531 nm are too far apart to allow for any confidence in the prediction of expected differences.

3. COMMON SOFTWARE APPROACH

The first step to achieving consistency in the derived nLw(λ) products between SeaWiFS and MODIS was to ensure standardization in the processing algorithms employed. The OBPG developed the Multi-Sensor Level-1 to Level-2 (MSL12) processing code (Feldman 2005), that was designed for the application of common atmospheric correction and normalization algorithms to a variety of ocean color sensors. MSL12 has been in use for SeaWiFS standard processing since the 3rd SeaWiFS reprocessing in 1999. The software is structured such that sensor-specific requirements are isolated in the Level-1 read function or external tables, thereby simplifying the integration of additional ocean color sensors. The table changes typically required are described in Wang (1999). The necessary changes were made to the software to recognize the MODIS Level-1B file format, and sensor-specific tables were added for the calculation of Rayleigh and aerosol reflectance at the MODIS spectral bands.

The MSL12 software also provides a standardized mechanism for vicarious calibration. The first step in the evaluation of any algorithm or instrument calibration changes is to perform a vicarious calibration (Eplee 2001) to the Marine Optical Buoy (MOBY, Clark 2001) located near Lanai, Hawaii. This effectively removes any mission-average bias in nLw(λ) due to error in the instrument calibration or atmospheric correction algorithm by forcing the normalized water-leaving radiance retrieval to match the *in situ* measurements at MOBY, on average. It should be emphasized that the vicarious calibration is independent of time, and that any temporal degradation is assumed to be accounted-for in the instrument calibration. For SeaWiFS and MODIS-Aqua, the vicarious calibration results in TOA radiance adjustments of no more than a few percent, which is an indication that the atmospheric correction algorithm, in combination with the pre-launch and on-orbit instrument calibration, is performing reasonably well as a system for the retrieval of water-leaving radiances.

The common software approach is also applied to Level-3 processing, where identical software and averaging methods are employed to generate spatial and temporal composites (Campbell 1995) for SeaWiFS and MODIS. This adds to consistency and greatly simplifies comparison of co-located retrievals between sensors.

4. INITIAL EVALUATION

When the OBPG assumed responsibility for MODIS oceans processing in February 2004, the SeaWiFS project was distributing a version of SeaWiFS ocean color products referred to as Reprocessing 4 (Patt 2003), and the Goddard Earth Sciences (GES) Distributed Active Archive Center (DAAC) was distributing MODIS-Aqua ocean products called Collection 3. With MODIS and SeaWiFS processing incorporated into a common framework, a major source of potential differences could be eliminated. The SeaWiFS Reprocessing 4 algorithms were applied to derive the nLw(λ) from MODIS-Aqua, and the initial results were evaluated for quality and consistency.

Figure 2 shows a comparison of MODIS-Aqua and SeaWiFS normalized water-leaving radiances as a function of time. These trends are derived from the global Level-3 products for each sensor, which were spatially averaged into approximately 9 x 9-km resolution equal-area bins and temporally averaged into consecutive 8-day composites (Campbell 1995). Specific bins were selected from each 8-day composite and averaged to make these time-series trends. The bin selection was limited to geographic locations where water depth is greater than 1000 meters (deep water), and only those bins with valid data for both sensors (common bins) were included in the averages.

Figure 2a shows the deep-water nLw(λ) trend comparison for MODIS-Aqua GES DAAC Collection 3 products relative to the 4th SeaWiFS Reprocessing. Significant differences can be seen in these trends, with the MODIS retrievals (dashed lines) elevated by approximately 20% relative to SeaWiFS and deviating more over time. Figure 2b shows the same trends derived by reprocessing the MODIS-Aqua data using the common software framework within the OBPG, including a vicarious calibration to MOBY. Comparing Figure 2a with Figure 2b, a dramatic improvement can be seen, but significant differences still remain, especially toward the end of the mission where the MODIS-Aqua trends tend to deviate from the SeaWiFS and generally decrease relative to the mission average values.

The trends in Figure 2b are presented as a ratio in Figure 3a, where the decrease in MODIS nLw(λ) relative to SeaWiFS is more apparent and a seasonal cycle is evident. The ratio trends also show a bifurcation in the relative agreement that can be compared to the expected differences in Figure 1. The mean chlorophyll concentration for the deep-water data set is approximately 0.2 mg/m^3, so we expect the MODIS 488 and 551-nm bands to be elevated relative to SeaWiFS by 2% and 6% respectively. The fact that the 488/490 ratio is elevated relative to the 443/443 ratio is in agreement with expectation, but the 412/412 ratio is not well behaved, and the 551/555 ratio appears to be biased low.

It was also found that the relative agreement between SeaWiFS and MODIS becomes significantly worse with increasing latitude. An example of this is Figure 3b, which shows the ratio of MODIS to SeaWiFS nLw(λ) retrievals derived by averaging a geographically limited region in the south eastern Pacific (89W-130.2W, 20.7S-44.9S). These regional trends show relative differences of ±10% with a strong seasonal cycle.

5. CALIBRATION AND ALGORITHM CHANGES

Starting with the results presented in Figure 3 and similar analyses, the OBPG began a systematic review of the pre-launch characterization and on-orbit calibration of the MODIS-Aqua instrument. Much of this work was done in close collaboration with the MODIS Characterization Support Team (MCST), which maintains responsibility for the MODIS instrument calibration. The following is a brief description of some of the more significant changes which have been made to MODIS calibration and the common processing algorithms to improve quality and consistency in the combined nLw(λ) retrievals.

5.1 MODIS Polarization Sensitivity

As described in Meister 2005a, the OBPG determined that the polarization sensitivity, as characterized for MODIS in pre-launch laboratory testing (Young 1998), had been misinterpreted when the polarization correction (Gordon 1997) was implemented within the original, MODIS-specific atmospheric correction code. Unlike SeaWiFS, which was designed with a polarization scrambler to minimize sensitivity to polarized light (Barnes 1994), the MODIS instrument suffers from significant polarization sensitivity, requiring corrections as large as 3% in the observed radiance of the most sensitive band, 412 nm. If uncorrected, this translates to roughly 30% error in nLw(412) retrievals. Meister found that the correction developed by Gordon was incorrectly implemented, and the effect was to increase rather than decrease the polarization-related error in the retrieved nLw(λ). The polarization of the light exiting the atmosphere generally increases with solar zenith angle, so errors due to polarization sensitivity increase with latitude. Meister re-analyzed the pre-launch polarization sensitivities and revised the correction method, and these changes were implemented in MSL12. Figures 4a and 4b show the nLw ratios of MODIS to SeaWiFS as a function of time for a high latitude region of the Pacific (150W-170W, 40N-50N), where a dramatic improvement in sensor agreement can be seen after the revised MODIS polarization correction was applied. The apparent over-correction of the 412-nm band in January 2003 was later found to be a MODIS stray light artifact.

5.2 MODIS Temporal Calibration

The MCST determines the extent of MODIS instrument change with time through analysis of direct lunar and indirect solar observations collected on a periodic basis (Xiong 2003, Xiong 2004). Knowledge of the instrument calibration has improved over time simply by virtue of additional measurements and the knowledge gained from on-going analysis of the instrument calibrator trends. In addition, the OBPG has worked closely with the MCST to re-evaluate the methods used for fitting the temporal trends, using the highly sensitive trends in ocean water-leaving radiances to help assess improvement. The OBPG is now using an alternate instrument calibration based on the most recent MCST on-orbit calibration with modifications described in Meister 2005b.

5.3 MODIS Stray Light Masking

Both MODIS and SeaWiFS experience some level of contamination from bright sources adjacent to the primary viewing direction. This stray light is characterized by the instruments Point Spread Function (PSF). The SeaWiFS PSF was well characterized in pre-launch laboratory testing (Barnes 1995), and an algorithm was developed to mask the largest contamination and correct for residual effects. Unfortunately, the pre-launch characterization of MODIS stray light contamination was limited to an analysis of the Line Spread Function (LSF) in the scan direction, so the along-track contamination is unknown. From the LSF and other information from the instrument manufacturer, the OBPG developed a model for the PSF (Meister 2005c). The model indicates that the central pixel typically measures only 66% of the correct intensity, with the rest coming from adjacent pixels. This means that low radiance ocean observations that are within a few kilometers of bright sources such as clouds, beaches, or sun glint will be heavily contaminated. Since uncertainty in the modeled PSF currently precludes its use for actually correcting the observations for stray light contamination, the OBPG decided to exclude (mask) from ocean color processing all observations within a few pixels of cloud or saturation-flagged pixels. The model estimates of the point-spread function for MODIS suggested that a 7x5-pixel masking (±3 pixels along scan, ±2 pixels along track) around these high-radiance pixels would eliminate the majority of the contamination. This represents a considerable data loss, but confidence in the remaining data is substantially enhanced. A direct impact of this additional masking was seen in the global deep-water aerosol optical thickness (AOT) comparisons with SeaWiFS. The atmospheric correction algorithm will categorize any unidentified signal in the NIR as aerosol scattering (Gordon & Wang 1994). Prior to masking of the MODIS stray light, the global deep-water averaged AOT retrievals were 50% higher than the equivalent SeaWiFS retrievals. Figures 5a and 5b show the AOT retrievals of MODIS and SeaWiFS before and after MODIS stray light masking. After the masking was implemented, the AOT retrievals for the two instruments agree to within a few percent.

5.4 Surface Reflection/Refraction Effects

MODIS and SeaWiFS will generally view the same location on the Earth at a different time of day and from a different viewing angle. In SeaWiFS Reprocessing 4, a correction was implemented to account for losses due to reflection and refraction of the upwelling radiance at the sea-to-air interface (Franz 2003). This correction, which varies with viewing angle, was already included in the initial MODIS processing by the OBPG. However, a related correction was added to the common processing software to account for reflection and refraction losses of the downwelling solar irradiance at the air-to-sea interface (Mobley 1994). This effect varies with the incidence angle (zenith angle) of the solar irradiance and with roughness of the ocean surface, which can be correlated with wind speed. M. Wang (private communication) modeled this effect and developed a correction algorithm that, when applied in the normalization of $Lw(\lambda)$, removes an error in previous SeaWiFS and MODIS $nLw(\lambda)$ products which can reach 5% or more at high solar zenith angles. In addition, the solar zenith angle varies with time of day as well as day of year for a fixed geographic location, so the downwelling reflection/refraction correction also removes a small source of variability between SeaWiFS and MODIS-Aqua $nLw(\lambda)$ related to differences in observation time.

5.5 Bi-Directional Reflectance

The distribution of upwelling radiance just below the ocean surface is generally not isotropic, and will change in response to variation in solar incidence angle in combination with the inherent optical properties of the water, particularly the volume scattering function (VSF). The anisotropy of the subsurface light field contributes to a spectrally-dependent variation in $Lw(\lambda)$ with viewing angle which was not taken into account in previous MODIS or SeaWiFS ocean color processing. Morel (2002) proposed a correction to remove this bi-directional effect as part of the normalization to $nLw(\lambda)$. Unlike the reflection/refraction effects, this correction varies with the concentration of scatterers in the water column (e.g., phytoplankton), and thus must be derived in an iterative fashion since such concentrations are not known *a priori*. The Morel approach uses intermediate retrievals of chlorophyll concentration to estimate the VSF, and pre-computed tables derived from radiative transfer simulations to determine the appropriate correction for a given solar and viewing geometry. The application of this correction has been found to improve consistency of $nLw(\lambda)$ with view angle and solar zenith angle. This correction removes a source of variability between SeaWiFS and MODIS-Aqua $nLw(\lambda)$ related to differences in observation time and viewing geometry.

6. REPROCESSING AND EVALUATION

The changes described in the previous section, as well as other less substantial changes, were incorporated into a full mission reprocessing of MODIS-Aqua and SeaWiFS ocean color data sets known as MODIS-Aqua Reprocessing 1 and SeaWiFS Reprocessing 5. Calibration and algorithm updates were introduced incrementally, so that the effect of each change could be predicted and the results verified. For each modification, the OBPG performed a comprehensive set of analyses to evaluate the impact to data quality and cross-sensor consistency. The evaluations included comparison with field data and analysis of mission-long temporal trends in mean water-leaving radiances on global and regional spatial-scales. When comparing products between sensors, any algorithm changes that were applicable to both sensors were applied equally, and both sensors were vicariously re-calibrated to MOBY. The results derived from this process helped to quantify the impact of processing changes on the global data set, and provided feedback for the ongoing instrument calibration and characterization efforts. Once calibration and algorithm changes were finalized, a full-mission reprocessing was initiated and completed in March 2005. The reprocessing included approximately 2.5 years of MODIS-Aqua data and 7.5 years of SeaWiFS data. Some validation results from this final reprocessing are presented next, including comparisons between the two sensor data sets over the common mission lifespan from July 2002 through December 2004.

6.1 Comparison to Ground Truth

A primary mechanism for assessing the quality of retrieved ocean color properties is comparison with ground-truth measurements. The OBPG maintains a comprehensive repository of *in situ* radiometric and pigment data known as the SeaWiFS Bio-optical Archive and Storage System (SeaBASS; Werdell & Bailey 2002, Werdell 2003). Currently, SeaBASS consists of oceanographic and atmospheric field data from over 1350 field campaigns contributed by researchers from 48 institutions in 14 countries. The comparison to field data provides a measure of the quality of satellite retrievals for a single, instantaneous observation. It is most useful as a tool for identifying systematic bias in satellite retrievals. Table 2 provides a statistical analysis of the nLw(λ) comparisons between *in situ* measurements and the satellite retrievals.

Wavelength		# Matches		Mean Ratio*		% Difference**		r^2		Bias***	
MODIS	SeaWiFS	MODIS	SeaWiFS	MODIS	SeaWiFS	MODIS	SeaWiFS	MODIS	SeaWiFS	MODIS	SeaWiFS
412	412	104	553	0.662	0.916	36.373	22.637	0.702	0.815	-0.307	-0.076
443	443	118	702	0.805	0.928	21.403	17.070	0.792	0.815	-0.194	-0.047
488	490	94	660	0.860	0.933	18.374	14.531	0.899	0.828	-0.149	-0.052
531	510	22	479	0.882	0.933	13.883	12.936	0.935	0.866	-0.234	-0.042
551	555	105	702	0.910	0.939	12.824	16.279	0.938	0.928	-0.095	-0.035
667	670	92	666	0.619	0.947	41.639	45.147	0.738	0.883	-0.031	-0.006

*arithmetic mean of all satellite / in situ ratios, ** median absolute percent difference, ***mean difference

Table 2: MODIS and SeaWiFS Comparison to Ground Truth.

These statistics are based on a match-up analysis described in McClain 2000, which includes extensive quality screening and tight restrictions on time difference between field measurements and satellite observations. For the bands between 443 and 555 nm, the results are quite comparable between sensors. It should be noted, however, that the number of match-up cases is significantly lower for MODIS-Aqua. This is due to the shorter mission lifespan of the Aqua platform, as well as a general reduction in relevant field data campaigns following the demise of the SIMBIOS program (Fargion 2003). This limitation on available match-ups contributes to greater uncertainty in the statistics, especially in the red bands where the available signal is very low. The comparatively degraded performance of MODIS at 412 nm may be an indication of residual error due to atmospheric polarization, as uncertainty exists in the modeling of atmospheric polarization effects (e.g., polarization due to aerosols is not considered), and the 412-nm band shows significant sensitivity to polarized light (Meister 2005a). The MODIS comparisons generally show a larger negative bias that is not yet understood.

It must be recognized that the temporal and geographic distribution of the *in situ* data set is limited (Werdell & Bailey 2005), so the *in situ* validation analysis is not sufficient for assessing the quality of remotely sensed ocean color data over the full range of geometries through which the spaceborne sensor views the Earth. Field data comparisons can not provide a complete assessment of quality over the temporal extent and geographic distribution of the OBPG global products, nor can they account for the effects of temporal and spatial averaging or systematic errors associated with Level-3 masking decisions. For this the OBPG looks at temporal trends in Level-3 products on global and regional spatial scales.

6.2 Temporal Self-Consistency Analysis

The deep-water trend analysis, as described in Section 4, can also be used to test the self-consistency of derived products from each sensor, by comparing the seasonal trends from one year to the next. Figures 6a and 6b present the annual trends in global deep-water nLw(λ) for SeaWiFS and MODIS-Aqua, respectively. A periodic cycle in these trends is expected, due to seasonal variations in phytoplankton growth (i.e., chlorophyll concentration) and the latitudinal extent of daylight (nLw retrievals for solar path geometries above 70-degrees zenith are not included in the Level-3 products). In the absence of any major geophysical events, the seasonal trends in global deep-water nLw(λ) can be expected to repeat from year to year. Small differences may be due to geographic sampling effects or real geophysical changes, but considering that the temporal calibration of SeaWiFS is based exclusively on trending of lunar observations (Eplee 2004), Figure 6a indicates that the instrument-level calibration is performing well. The deviations seen in the first few months of the mission (1997) may be due to increased uncertainty in correcting the initial degradation of the SeaWiFS sensor response, or increased error in the aerosol correction due to extensive fires in Indonesia at that time. The MODIS-Aqua self-consistency analysis is less reliable, as only 2.5 annual cycles are available for comparison. Figure 6b suggests that, like SeaWiFS, MODIS-Aqua trends were also less consistent in the first few months of the mission (2002), in comparison to subsequent years. In addition, the mid-mission period in the second half of 2003 shows a negative bias relative to previous and subsequent years. It is suspected that this mid-mission bias is related to trending error in the instrument temporal calibration, but investigation is continuing.

6.3 Global and Regional Sensor-to-Sensor Temporal Trends

The final analysis presented here examines direct comparisons between SeaWiFS and MODIS-Aqua as a function of time. Taken alone, this comparative temporal analysis can not be used to determine absolute error, since relative differences may be due to errors in either sensor data set, or real geophysical effects related to disparity in observation times. However, when taken in concert with the self-consistency analyses and the *in situ* comparisons, the sensor-to-sensor comparisons can serve to identify and isolate the likely cause for differences. Figure 7a shows the ratio of MODIS to SeaWiFS deep-water nLw(λ) as a function of time for SeaWiFS Reprocessing 5 and MODIS-Aqua Reprocessing 1. The ratio trends show that MODIS-Aqua and SeaWiFS global averaged deep-water nLw(λ) retrievals are in agreement to within 5% in the 400-600 nm range. In general, the ratios indicate that MODIS-Aqua retrievals are biased low relative to SeaWiFS, just as they were biased low relative to *in situ* measurements. The negative bias is largest near the mid-point of the Aqua mission, as was suggested by the self-consistency analysis of Figure 6b which showed MODIS to be biased low at this time relative to preceding and subsequent years. The data used to produce Figure 6b was also used to generate the summary statistics of Table 3. Ignoring the overall bias, these results show the 551/555 ratio and the 488/490 ratios to be elevated relative to the 443/443 ratio, on average, which is consistent with expectation. The nLw(412) ratio between the two sensors is less consistent than the other visible bands, perhaps due to residual error in the polarization correction for MODIS. In clear water, the water-leaving radiance signal in the red channels is very small, with variations approaching the 1-count digitization level of the SeaWiFS instrument, so the poor agreement and general lack of correlation in the red is understandable. It is interesting to note, however, that the MODIS nLw(667) is 40% low relative to SeaWiFS and relative to the *in situ* comparison.

Wavelength		Mean Ratio*	% Difference**	r^2	Bias***
MODIS	SeaWiFS				
412	412	0.981	1.84	0.890	-0.0332
443	443	0.953	5.11	0.890	-0.0724
488	490	0.982	2.09	0.868	-0.0200
551	555	0.995	1.79	0.703	-0.0016
667	670	0.578	39.8	0.0138	-0.0161

* arithmetic mean of MODIS/SeaWiFS ratios, ** median absolute percent difference, ***mean difference

Table 3: Statistical Comparison of MODIS Deep-Water nLw to SeaWiFS

Finally, Figure 7b shows the comparison between MODIS-Aqua and SeaWiFS nLw retrievals for the southeastern Pacific region. By comparing this with Figure 3b, it can be seen that the seasonal differences between MODIS and SeaWiFS products have been significantly reduced. Based on incremental test results, the OBPG found this improved agreement was primarily a result of the additional bi-directional reflectance corrections. Residual seasonal effects may be due to error in this bi-directional reflectance model, or other issues not yet identified.

7. CONCLUSIONS

The Ocean Biology Processing Group was formed from the SeaWiFS and SIMBIOS projects to consolidate the calibration, validation, processing, and distribution of NASA's remote sensed ocean color measurements. The OBPG absorbed the MODIS-Aqua ocean color data processing into the existing SeaWiFS production system, and began a process of systematic updates and evaluations with a focus on improving the quality and consistency of water-leaving radiance retrievals from the two sensors. This process resulted in a set of calibration and algorithm changes that were applied in a multi-mission ocean color processing and redistribution known as MODIS-Aqua Reprocessing 1 and SeaWiFS Reprocessing 5. The resulting normalized water-leaving radiance products were shown to be in agreement to 5% on the global average, with seasonal and regional differences substantially reduced. Some remaining discrepancies were identified and potential areas of improvement for the next reprocessing were discussed.

The evaluations presented here are just a fraction of the many tests and analyses performed by the OBPG to verify the quality and consistency of the multi-mission ocean color data set. Advancements in MODIS instrument characterization are continuing, with work currently focused on reducing cross-scan and detector-to-detector striping artifacts in the MODIS imagery. At the time of this latest reprocessing, the SeaWiFS mission had been discontinued as a cost savings measure. Acquisition of SeaWiFS data has since resumed, and the OBPG is maintaining the forward-stream processing of both ocean color data sets. In addition, the Project is engaged in a similar reanalysis of the data collected by the Japanese Ocean Color and Temperature Scanner (OCTS), and working toward a reprocessing of the mission that started it all, CZCS.

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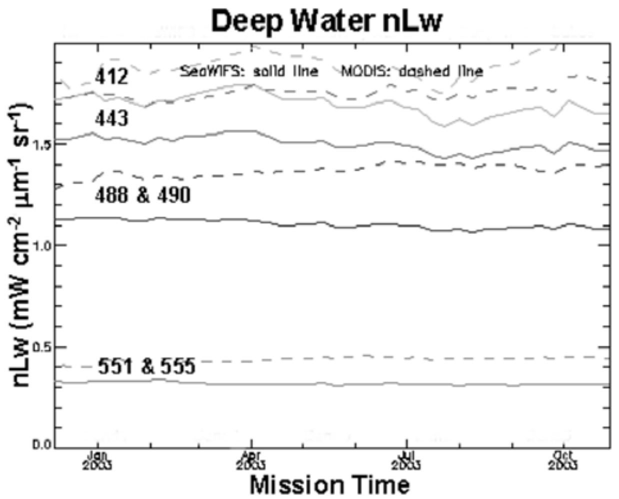


Figure 2a: Comparison of SeaWiFS Reprocessing 4 (solid line) and MODIS-Aqua Collection 3 (dashed line) normalized water-leaving radiance trends before application of common software and calibration approach.

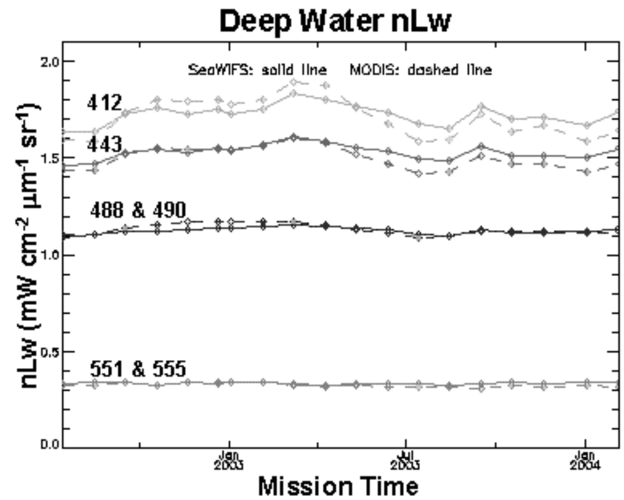


Figure 2b: Comparison of SeaWiFS Reprocessing 4 (solid line) normalized water-leaving radiance trends with MODIS-Aqua (dashed line) after initial OBPG reprocessing of MODIS using a common software and calibration approach.

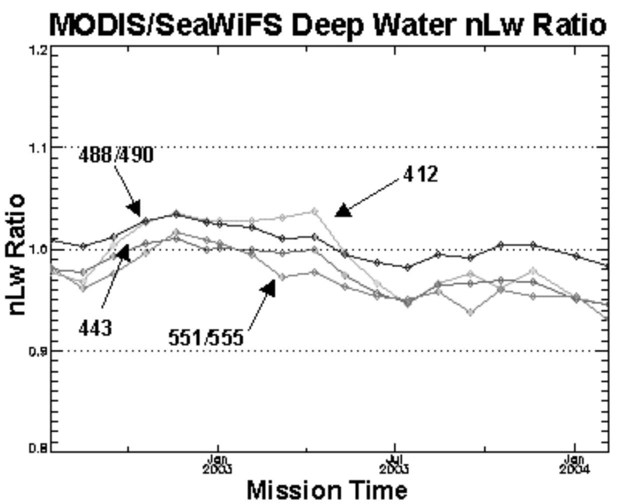


Figure 3a: Ratio of MODIS-Aqua deep-water mean normalized water-leaving radiances to SeaWiFS after initial OBPG reprocessing.

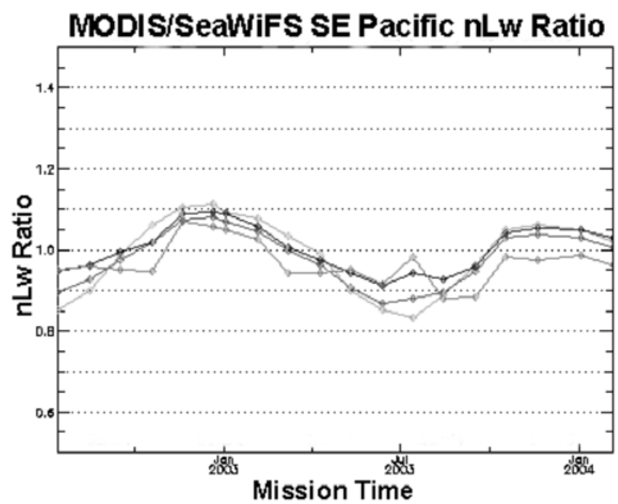
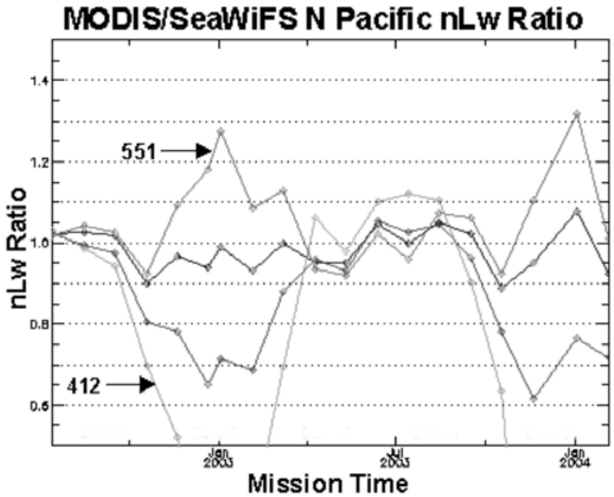


Figure 3b: Ratio of MODIS-Aqua south-east Pacific regional mean normalized water-leaving radiances to SeaWiFS after initial OBPG reprocessing.



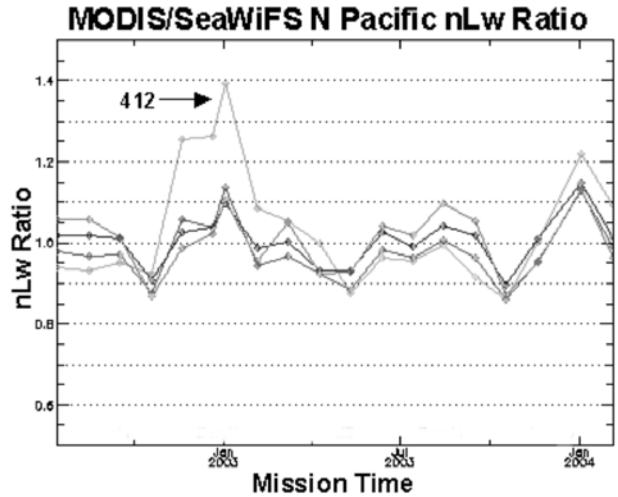
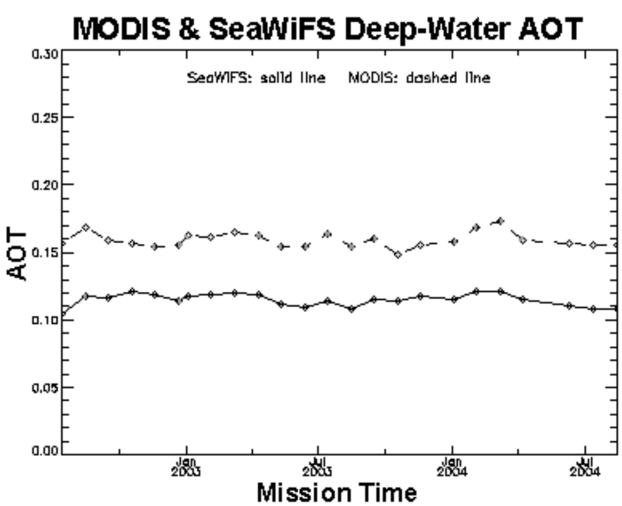


Figure 4a: Ratio of MODIS-Aqua northern Pacific regional mean normalized water-leaving radiances to SeaWiFS, before revised MODIS polarization correction.

Figure 4b: Ratio of MODIS-Aqua northern Pacific regional mean normalized water-leaving radiances to SeaWiFS, after revised MODIS polarization correction



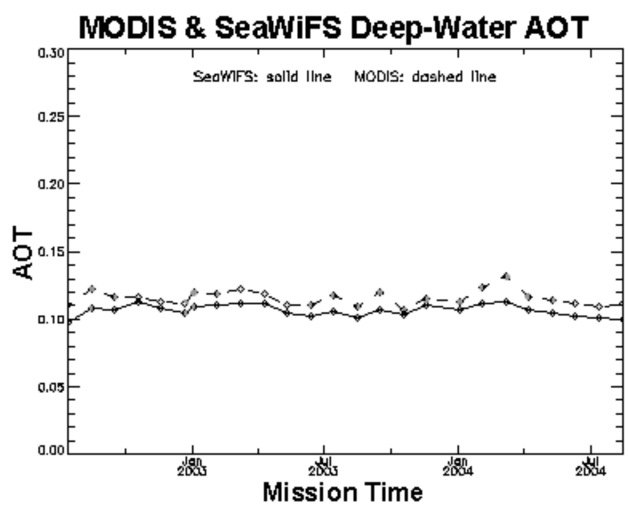


Figure 5a: Ratio of MODIS-Aqua deep-water mean aerosol optical thickness retrieval at 869 nm to SeaWiFS, before MODIS stray light masking.

Figure 5b: Ratio of MODIS-Aqua deep-water mean aerosol optical thickness retrieval at 869 nm to SeaWiFS, after MODIS stray light masking.

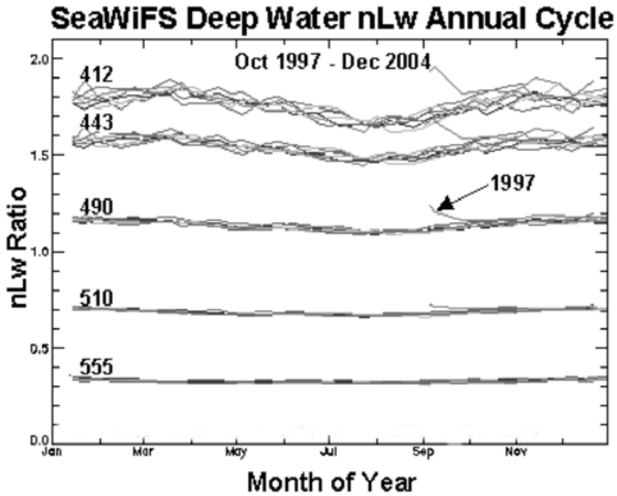


Figure 6a: Trends in SeaWiFS Reprocessing 5 deep-water mean normalized water-leaving radiances, presented as an annual repeat cycle to show year to year consistency.

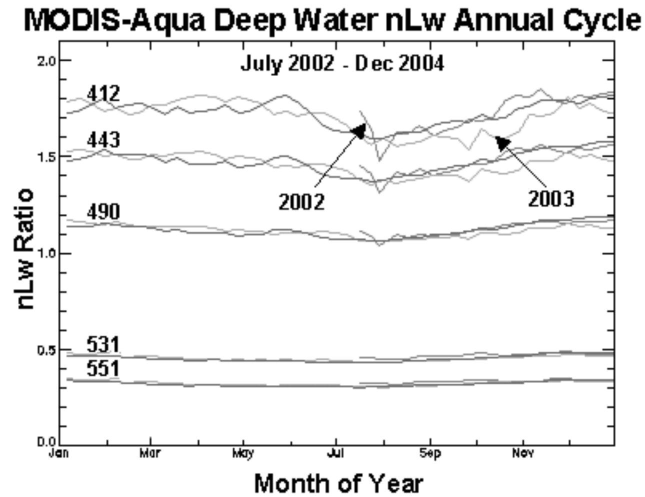


Figure 6b: Trends in MODIS-Aqua Reprocessing 1 deep-water mean normalized water-leaving radiances, presented as an annual repeat cycle to show year to year consistency

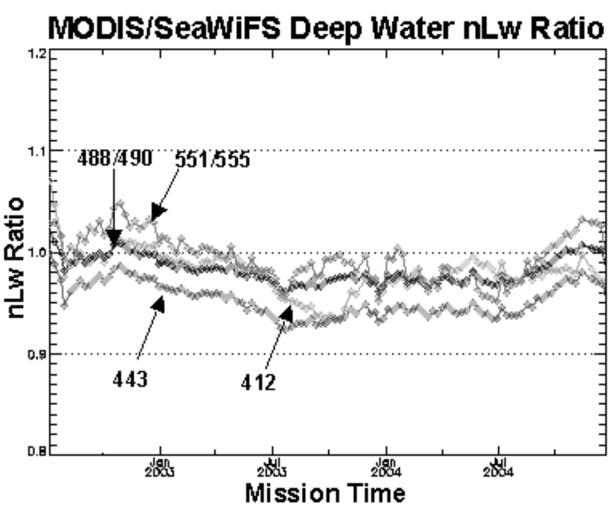


Figure 7a: Ratio of MODIS-Aqua Reprocessing 1 deep-water mean normalized water-leaving radiances to SeaWiFS Reprocessing 5.

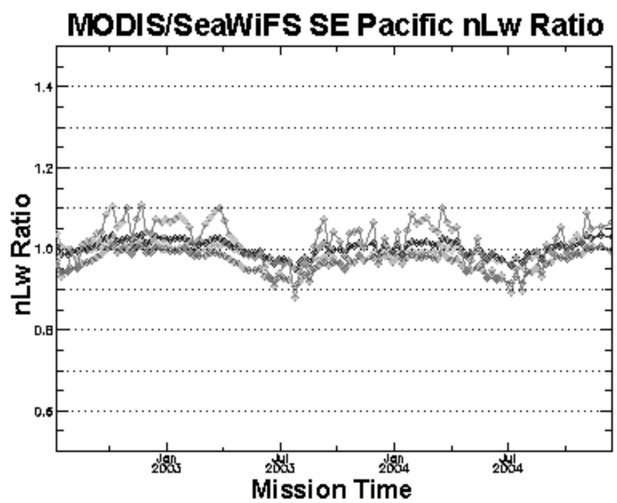


Figure 7b: Ratio of MODIS-Aqua Reprocessing 1 south-east Pacific regional mean normalized water-leaving radiances to SeaWiFS Reprocessing 5.