VIIRS OCEAN COLOR RESEARCH AND APPLICATIONS

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ABSTRACT

In this paper, we provide evaluations and assessments of the Visible Infrared Imaging Radiometer Suite (VIIRS) ocean color products, including normalized water-leaving radiance spectra $nL_w(\lambda)$ at VIIRS five spectral bands, chlorophyll-a concentration (Chl-a), water diffuse attenuation coefficients at the wavelength of 490 nm, $K_d(490)$, and at the domain of photosynthetically available radiation (PAR), $K_d(\text{PAR})$. Specifically, VIIRS ocean color products derived from the NOAA Multi-Sensor Level-1 to Level-2 (MSL12) ocean color data processing system are evaluated and compared with in situ data from the Marine Optical Buoy (MOBY) and measurements from the Moderate Resolution Imaging Spectroradiometer (MODIS). In general, VIIRS ocean color products are matched well with MOBY in situ measurements, and are also consistent with those from MODIS-Aqua. Ocean color products were found to be highly sensitive to some operational sensor calibration issues. We have improved sensor calibration by combining the lunar calibration into the current calibration method. Here, the ocean color products based on the new sensor calibration are evaluated. Our results show that VIIRS is capable of providing high-quality global ocean color products in support of the scientific research and operational applications.

***Index Terms*—** VIIRS, ocean color data, calibration, validation

1. INTRODUCTION

The Visible Infrared Imaging Radiometer Suite (VIIRS) on the Suomi National Polar-Orbiting Partnership (SNPP) was launched on October 28, 2011. The VIIRS Ocean Color Team at NOAA Center for Satellite Applications and Research (STAR) has been routinely processing and evaluating VIIRS ocean color products from the start of the VIIRS mission. We have developed a global near-real-time (NRT) ocean color data processing system that automatically downloads global VIIRS Raw Data Records (RDR or Level-0 data), Sensor Data Records (SDR or Level-1B data), and ancillary data in NRT and then processes them into ocean color Environmental Data Records (EDR or Level-2 data). The NOAA Multi-Sensor Level-1 to Level-2 (NOAA-MSL12) software package is used for VIIRS ocean color SDR-to-EDR processing. The global Level-3 binned products (daily, 8-day, monthly, and climatology) are also generated routinely for evaluation. For the purpose of sensor calibration, the system is also flexible for reprocessing VIIRS data from RDR to SDR, and subsequently from SDR to ocean color EDR.

For monitoring and evaluation, VIIRS ocean color EDR data are routinely compared with in situ data from the Marine Optical Buoy (MOBY) in waters off Hawaii [1], and several AERONET-OC sites around the world (http://aeronet.gsfc.nasa.gov). The VIIRS ocean color EDR time series in global oligotrophic waters (where chlorophyll-a concentrations (Chl-a) are < 0.1 mg m^{-3}) and in global deep water regions (where depths are > 1 km), and several other regions of interest, such as South Pacific Gyre, U.S. east coast, North and South Pacific oceans, etc., are also routinely monitored and compared with measurements from the Moderate Resolution Imaging Spectroradiometer (MODIS) on the satellite Aqua. Some initial evaluations and assessments of VIIRS ocean color data produced by the NOAA ocean color team have been reported by *Wang et al.* (2013) [2] and in some other recent studies [3]. In this paper, we provide updates on the evaluations of VIIRS ocean color products with longer time series, more in situ data for matchup analysis, and improved sensor calibration.

2. DATA AND METHOD

2.1. VIIRS RDR and SDR Data from IDPS

The VIIRS RDR (or Level-0 data) and SDR (or Level-1B data) are downloaded routinely from the SNPP central technical support infrastructure GRAVITE and the NOAA Comprehensive Large Array-data Stewardship System (CLASS). The VIIRS operational SDR data, which are produced from the NOAA Interface Data Processing System (IDPS), include the top-of-atmosphere (TOA) radiance and reflectance from VIIRS bands M1 to M11, geo-location data, and on-board-calibration intermediate products. All VIIRS data started from November 21, 2011 to present have been downloaded to generate VIIRS ocean color EDR products.

2.2. MSL12-Derived Level-2 Ocean Color Products

The MSL12 ocean color data processing package has been developed based on the SeaDAS version 4.6, which has been used to process various satellite ocean color data from the Level-1 to Level-2, e.g., SeaWiFS, MODIS, etc. MSL12 has been enhanced to include the function to process ocean color data from VIIRS. The input data for MSL12 include VIIRS SDR data from M1 to M7 and the shortwave infrared (SWIR) bands M8, M10, and M11, geo-location data, and ancillary input data. The output products include normalized water-leaving radiance spectra $nL_w(\lambda)$ for VIIRS M1 to M5 bands, Chl-a, $K_d(490)$, $K_d(\text{PAR})$, inherent optical properties (IOPs), etc., as well as various Level-2 data quality flags. MSL12 essentially uses the *Gordon and Wang* (1994) [4]

atmospheric correction algorithm. For turbid coastal and inland waters, the new near-infrared (NIR) ocean reflectance correction algorithm (named BMW) [5] is used. The K_d(PAR) is a new operational product described in *Son and Wang* (2015) [6]. Furthermore, to deal with the striping issue in the VIIRS ocean color product imagery, we have developed a post-processing destriping algorithm for the improved VIIRS ocean color Level-2 outputs [7].

2.3. MSL12-Derived Level-3 Ocean Color Products

The global NRT ocean color data processing system in NOAA STAR also processes VIIRS Level-2 EDR data into global Level-3 data. The Level-3 data processing algorithm is essentially the same as the one used for producing SeaWiFS and MODIS global Level-3 ocean color products by NASA. Currently, VIIRS ocean color EDR data are processed routinely into global Level-3 data with 9-km spatial resolution (daily, 8-day, monthly, and climatology).

2.4. MODIS-Aqua Level-3 Ocean Color Data

Daily, 8-day, and monthly MODIS-Aqua Level-3 4-km binned ocean color data are downloaded online from the NASA Ocean Biology Processing Group web site (oceancolor.gsfc.nasa.gov). MODIS-Aqua Level-3 data are compared with those from VIIRS in global oligotrophic waters, global deep waters, and several ocean regions around the world.

2.5. In Situ Data

In situ radiometric data measured by MOBY [1] moored off the island of Lanai in Hawaii are used to evaluate VIIRS SDR and ocean color EDR products. The MOBY program has been providing high-quality ocean optics data to support various satellite ocean color missions, particularly for SeaWiFS, MODIS, and now VIIRS. The in situ $nL_w(\lambda)$ measurements at the VIIRS-spectrally-weighted wavelengths, i.e., effective wavelengths at about 410, 445, 485, 548, and 653 nm are used to evaluate and assess VIIRS SDR and ocean color EDR products. For matchup comparison, the VIIRS-measured $nL_w(\lambda)$ and Chl-a data were extracted from Level-2 data files using an 5×5 box centered at the location of in situ measurements. For Chl-a comparison, MOBY in situ $nL_w(\lambda)$ data were used to derive Chl-a data using the same VIIRS OC3V Chl-a algorithm in the MSL12 ocean color data processing.

3. RESULTS

3.1. Global Climatology Images

Global VIIRS climatology images of Chl-a concentration, $K_d(490)$ and K_d(PAR) are shown in Fig. 1. In general, VIIRS Chl-a data (top panel) provide similar spatial distributions as those from MODIS-Aqua (not shown here): Chl-a are low in the centers of major ocean circulation gyres, such as South Pacific gyre, and high in high latitudes of both north and south hemisphere, and equatorial regions. For $K_d(490)$ (middle panel), VIIRS data are equivalent to MODIS-Aqua in most of open oceans. However, in turbid coastal waters, such as along the China east coast, MSL12-derived $K_d(490)$ data are significantly improved (significantly higher) compared to those from MODIS-Aqua. K_d(PAR) (lower panel) is a new product in MSL12 [6]. It has been evaluated with various in situ measurements around the world ocean and will be used by the National Center for Environmental Prediction (NCEP) in future operational ocean forecast models to improve the global sea surface temperature (SST) and mixed layer ocean dynamics.

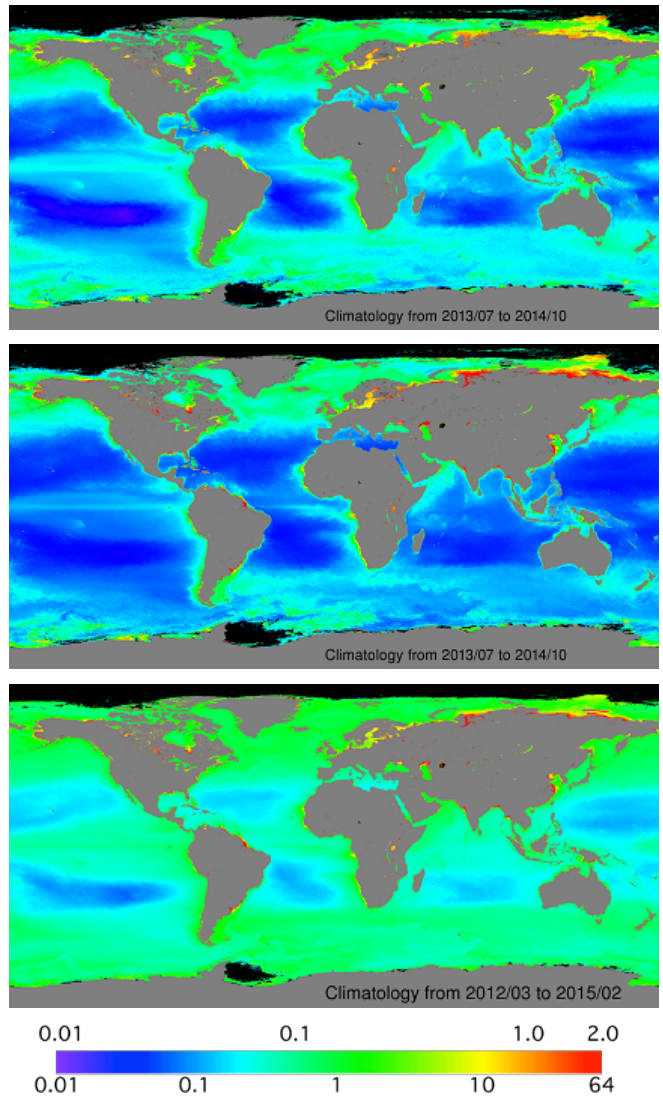

Figure 1. Global climatology images (all in log scale) of Chl-a (top panel, 0.01–64 mg m^{-3}), $K_d(490)$ (middle panel, 0.01–2.0 m^{-1}), and K_d(PAR) (lower panel, 0.01–2.0 m^{-1}).

3.2. Comparison with MOBY In Situ Data

Time series of the MSL12-derived VIIRS $nL_w(\lambda)$ and Chl-a data, corresponding to MOBY in situ measurements, are constructed for the Hawaii MOBY site (20.5°N–21.5°N and 157.5°W–156.5°W) and compared with those from in situ data for assessments of the VIIRS observations. The time series of MSL12-derived $nL_w(\lambda)$ at wavelengths of 410 nm (M1), 443 nm (M2), 486 nm (M3), 551 nm (M4), and Chl-a compared with those from MOBY in situ measurements for the VIIRS period of January 2012 to December 2014, and the results show that the VIIRS ocean color products have a poor data quality before February 6, 2012, due to the incorrect use of the pre-launch F-factor look-up-tables (F-LUTs) for the SDR calibration [2]. On-orbit calibration was applied in IDPS RDR to SDR data processing since February 6, 2012. However, there were still higher values in VIIRS ocean color products between February 6 and April 20, 2012. The vicarious

calibration gains using the MOBY in situ measurements were applied after April 20, 2012. The VIIRS ocean color products were significantly improved after April 20, 2012, indicating the importance of vicarious calibration. In general, the MSL12-derived $nL_w(\lambda)$ data correspond well to MOBY in situ values in most of wavelengths. Table 1 shows the quantitative comparison between VIIRS and MOBY in situ data from January 1, 2012 to December 31, 2014.

Table 1. Average (AVG), standard deviation (STD), and number of data (No) of the ratio of VIIRS vs. MOBY in situ data for $nL_w(\lambda)$ at VIIRS M1–M5 bands and Chl-a from the operational IDPS SDR and the original MSL12 [2].

Products	AVG	STD	No
$nL_w(410)$	1.0134	0.138	388
$nL_w(443)$	1.0332	0.275	413
$nL_w(486)$	1.0377	0.301	413
$nL_w(551)$	1.1217	0.820	413
$nL_w(671)$	1.8842	3.126	424
Chl-a	1.0674	0.719	413

3.3. New VIIRS EDR Data Reprocessed from IDPS SDR

Since there were various changes (e.g., algorithms and vicarious gains) during the routine VIIRS ocean color processing, we have reprocessed the global ocean color data from the beginning of the VIIRS mission using IDPS SDR with the latest version of MSL12. By using consistent EDR algorithms and vicarious gains for the entire mission, the effect of SDR performance on the ocean color EDR can be evaluated. The reprocessed new ocean color EDR data are compared with MOBY in situ measurements, and the results are shown in Table 2. Table 2 shows that $nL_w(\lambda)$ and Chl-a data are both improved, and the improvements are mainly due to improved EDR algorithms and consistent vicarious gains.

Table 2. Same as Table 1, but EDR data were reprocessed using the latest/improved MSL12 and consistent vicarious gains with the operational IDPS SDR.

Products	AVG	STD	No
$nL_w(410)$	1.0045	0.102	363
$nL_w(443)$	1.0274	0.194	375
$nL_w(486)$	1.0356	0.209	375
$nL_w(551)$	1.0977	0.553	375
$nL_w(671)$	1.4441	2.419	389
Chl-a	1.0959	0.465	375

The reprocessed EDR data are also compared with MODIS-Aqua data at around MOBY location. Figure 2 shows the comparison of time series of VIIRS $nL_w(443)$, $nL_w(486)$, $nL_w(551)$ with those of MODIS-Aqua. In general, VIIRS $nL_w(\lambda)$ data in Fig. 2 are compared well and close to those of MODIS-Aqua after April 20, 2012. However, VIIRS $nL_w(\lambda)$ data are significantly higher than those of MODIS-Aqua before April 20, 2012 due to sensor calibration issue [2].

Figure 2. Time series of reprocessed VIIRS ocean color EDR data (red) compared with those of MODIS-Aqua (green) (30-day running means) for $nL_w(443)$ (top panel), $nL_w(486)$ (middle panel), and $nL_w(551)$ (lower panel) (units in mW cm^{-2} µm^{-1} sr^{-1}).

3.4. Sensor Calibration Issue

In Sections 3.2 and 3.3, we showed that there were some sensor calibration errors in the VIIRS IDPS SDR. In addition, we also found significant differences between year 2012 and 2013 in VIIRS ocean color EDR data due to sensor calibration issue [8], which leads to significantly low VIIRS $nL_w(\lambda)$ at 551 nm and consequently to the notable underestimation of VIIRS Chl-a in 2013 over global oligotrophic waters in comparison to those from MODIS-Aqua [8].

To resolve the sensor calibration issue, we put considerable effort into sensor calibration by re-examining and fixing errors in the current calibration methods, in particular, adding the effect of lunar calibration [9-11]. The VIIRS reflective solar bands (RSB) on-orbit gain changes are also monitored with scheduled monthly lunar observations through the instrument's space view (SV). The lunar observation tracks the VIIRS RSB gain change at the same angle of incidence (AOI) as for the SD calibration and thus, in principle, the two should provide the same on-orbit gain for all

RSB. In general, the derived lunar F-LUTs are consistent with those derived from the SD/SDSM observations. However, there are observable differences between the lunar and the SD F-LUTs, especially for short wavelength bands [11]. The differences between the two sets of calibration coefficients increase with time and are band dependent. For short wavelength bands, the differences are around 1% [11]. Since the Moon is more stable than the SD over the long-term, we have combined the two sets of calibration coefficients to generate a set of the LUTs for VIIRS RSB on-orbit calibration [11].

To evaluate our sensor recalibration work, the newly derived F-LUTs for VIIRS RSB have been used to reprocess from RDR to SDR, and then from SDR to ocean color EDR in the Hawaii (MOBY) region. The ocean color EDR based on recalibrated SDR data are compared with MOBY in situ data, and the results are presented in Table 3. Results show that the new calibration has significantly improved ocean color EDR data compared with the results in Table 2, and the improvements are due to new sensor calibration. This is consistent with a recent study from NASA group [12].

Table 3. Same as Table 1, but EDR data were derived using the latest MSL12 and consistent vicarious gains with our recalibrated SDR.

Products	AVG	STD	No
$nL_w(410)$	1.0115	0.101	414
$nL_w(443)$	1.0080	0.096	414
$nL_w(486)$	1.0089	0.089	414
$nL_w(551)$	1.0157	0.135	414
$nL_w(671)$	1.0638	0.525	428
Chl-a	1.0175	0.163	414

4. CONCLUSION

In this study, VIIRS ocean color EDR products derived from operational IDPS SDR and using MSL12 ocean color data processing system are evaluated. In general, the ocean color EDR products are compared well with in situ measurements from MOBY and are also consistent with those from MODIS-Aqua after April 20, 2012. Improvements of ocean color EDR algorithms and fine-tuning of vicarious gains have significantly improved the accuracy of VIIRS ocean color products. Sensor calibration issues are also found to lead to the difference between 2012 and 2013 in ocean color products. To resolve these issues, the current VIIRS SD/SDSM-based calibration methods were re-examined. The lunar calibration data were combined with VIIRS solar-based calibration to generate a new set of F-LUTs for VIIRS RSB. Furthermore, the new F-LUTs were used to reprocess VIIRS RDR to SDR, and SDR to ocean color EDR in the MOBY location. Compared with in situ data from MOBY, the reprocessed ocean color EDR products based on the new sensor calibration are significantly improved.

Given the improved performance of the new VIIRS sensor calibration, the NOAA Ocean Color Team is preparing for a global mission-long reprocessing from RDR to SDR, and SDR to ocean color EDR. The new derived F-LUTs will provide stable sensor calibration so that the correct and consistent ocean color EDR products can be derived from the starts of VIIRS mission. Thus, VIIRS can provide continuity and consistency ocean color data from SeaWiFS and MODIS for a long-term science-quality ocean color data record. In conclusion, our evaluation results show that VIIRS is capable of providing high-quality global ocean color products in support of the science research and operational applications.

Please visit VIIRS ocean color imageries and Cal/Val website at: http://www.star.nesdis.noaa.gov/sod/mecb/color/.

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