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Improving the consistency of ocean color data: A step toward climate data records

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[1] Two ocean color missions, SeaWiFS and MODIS, overlap in time and are processed with consistent methods. Global annual median chlorophyll from SeaWiFS and MODIS differ by 12.2%. These discrepancies exceed the maximum observed interannual variability globally and in every major oceanographic basin. Estimates of trends are affected as well. For 1998–2007 the SeaWiFS global trend is −2.6% (not statistically significant). Substitution of MODIS for SeaWiFS in 2003–2007 produces a −18% significant trend. A new approach that incorporates in situ data improves the consistency of the two sensor data sets. The global difference is −0.6% and the 10-year trend of SeaWiFS and MODIS agrees with standalone SeaWiFS (−3.3%, not significant). In oceanographic basins where sampling biases are small the differences are less than the maximum observed interannual variability. The approach improves the consistency of multiple successive ocean color missions and represents a step toward scientifically reliable Climate Data Records. **Citation:** Gregg, W. W., and N. W. Casey (2010), Improving the consistency of ocean color data: A step toward climate data records, *Geophys. Res. Lett.*, *37*, L04605, doi:10.1029/2009GL041893.

1. Introduction

[2] The state of ocean biology, represented by chlorophyll and observed globally by ocean color sensors, is an important indicator of climate change. Although there have been several efforts to document changes in ocean chlorophyll observed by satellite, nearly all are limited to a single sensor [*McClain et al.*, 2004; *Gregg et al.*, 2005; *Behrenfeld et al.*, 2006; *Polovina et al.*, 2008]. Observing climate change requires multiple, successive missions, since the operational lifetime of any sensor is finite (typically about 10 years). There are fewer efforts attempting to document changes across two missions [*Gregg and Conkright*, 2002; *Gregg et al.*, 2003; *Antoine et al.*, 2005; *Kahru and Mitchell*, 2008]. This is a much greater challenge, because all of the ocean color missions flown to date (and also proposed) differ greatly in design, capability, and sampling. Yet it is this challenge that must be met if we are to successfully observe climate change using satellite sensors.

[3] Previous efforts describing changes using two or more ocean color sensors have assumed that consistency in processing algorithms is sufficient to produce consistency in observations, and any deviations between the two observations are derived from natural variability. This assumption has not been tested, however, and it remains an assertion inherent in the methods.

[4] Two ocean color missions, the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) and the Moderate Resolution Imaging Spectroradiometer (MODIS) on the Aqua satellite overlap for the period 2003 through 2007. Both sensors are processed by NASA using the same pre- and post-launch calibration and algorithms. In a diagnostic comparison of the chlorophyll from these two sensors, *Morel et al.* [2007] found consistency over moderate to high ranges of the chlorophyll concentration spectrum, but deviations at the low end. We explore here how these differences translate into the representation of global and large scale regional biology, and in decadal trends. We substitute MODIS data for SeaWiFS when it became available in 2003 to test for the quality of temporal consistency, which is needed for satellite data to ensure unbiased interpretation of climate change.

[5] We additionally investigate the ability of a new approach to satellite ocean color data, the Empirical Satellite-In situ Data (ESRID) algorithm [*Gregg et al.*, 2009], to reduce the discrepancies between the two sensor data sets. Previously, ESRID was shown to improve the bias of SeaWiFS data and reduce the need for post-launch re-calibration. Here we apply the approach to two sensor data sets, SeaWiFS and MODIS, in an attempt to improve their consistency and promote their use as ocean biology Climate Data Records (CDRs).

2. Methods

[6] SeaWiFS and MODIS Level-3 9 km Standard Mapped Image chlorophyll data were obtained from the NASA Ocean Color Web beginning in late 2007. Daily data were averaged to produce monthly means. Data <5 m bottom depth were excluded to minimize the contribution of inland lakes. The monthly mean data were then averaged over 12 months to produce annual means and remove the influences of the seasonal signal. The central tendency was represented by the median of the annual mean chlorophyll fields. This is reported globally and regionally over the 12 major oceanographic basins (Figure 1).

[7] Trends were described by linear regression of annual median chlorophyll. The change was represented using the chlorophyll estimated by the regression: the estimated chlorophyll in the last year (2007) minus the first year (1998), as a percent of the first year estimated chlorophyll. We evaluated trends in two ways: 1) SeaWiFS from 1998 to 2007, and 2) a combination where SeaWiFS data were used from 1998 through 2002, then replaced by MODIS data from 2003 until 2007. The trend statistics included the linear equation and the standard error of the estimate.

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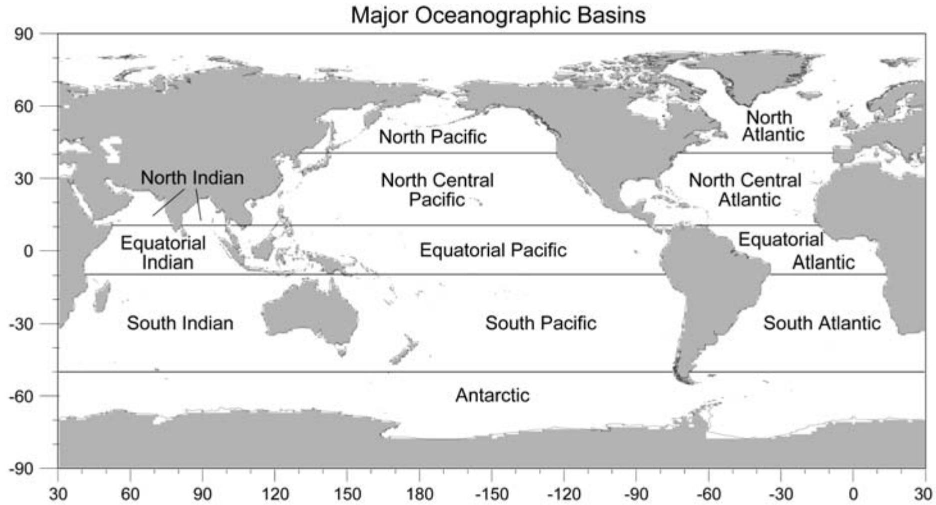

Figure 1. Delineation of the major oceanographic basins.

[8] In an effort to improve the consistency of the SeaWiFS and MODIS data, we applied the ESRID algorithm [*Gregg et al.*, 2009], a new approach for producing derived geophysical products. The approach is entirely empirical. It uses satellite water-leaving radiances and derives relationships with co-located, coincident in situ data. ESRID is applied a posteriori to the standard data processing procedure. In short, the approach re-derives the bio-optical algorithm of SeaWiFS and MODIS, but uses derived satellite water-leaving radiances instead of in situ radiances. The empirical coefficients derived in this manner absorb biases in the satellite radiances, which include those arising from calibration and sensor design. In previous work, ESRID was shown to 1) reduce the bias of ocean chlorophyll estimates from SeaWiFS, 2) modestly improve the uncertainty, and 3) reduce the sensitivity of global annual median chlorophyll to changes in post-launch radiometric re-calibration and other sources of bias.

[9] Contemporaneous in situ fluorometric chlorophyll data sets from the National Oceanographic Data Center (NODC) [*Conkright et al.*, 2002], NASA in situ [*Werdell and Bailey*, 2005], and Atlantic Meridional Transect [*Aiken et al.*, 2000] archives, were obtained and quality controlled [*Gregg et al.*, 2009]. New in situ data from the public archives increased the total from 53588 to 132964. ESRID was applied to both the SeaWiFS and MODIS data sets using these in situ data.

[10] Sampling differences from the two sensors were considered by computing the fraction of 9 km bins observed by one sensor but not the other for the period 2003–2007. This was done on a monthly basis to expose sampling differences that may not appear in the annual data, but may be important contributors to the annual median. Any basin for which >25% of the data from one sensor was not observed by the other in any month was considered suspect. These results were buttressed by an analysis of sampling biases of MODIS and SeaWiFS relative to assimilation data that represented full sampling [*Gregg and Casey*, 2007]. Although these previous results did not include inter-comparison between the sensor sampling, together with the analyses here they provide evidence of sampling issues.

[11] All analyses were for the period 1998 (the first full year of SeaWiFS) through 2007. For perspective, differences in global annual median chlorophyll from SeaWiFS and MODIS were compared to the maximum interannual variability observed in the SeaWiFS record for 1998–2007. We calculated the maximum positive and negative departures from the SeaWiFS climatological mean of the annual medians. We used the mean of the departures as an indicator of the magnitude of interannual variability. This was evaluated globally and for each oceanographic basin.

3. Results

[12] The mean difference in global annual median chlorophyll (MODIS-SeaWiFS) using the NASA standard method is −12.2% (Figure 2). The difference varies from −10.5% in 2006 to −12.9% in 2005 (Figure 2). When using ESRID, the mean difference improves to −0.6%. The major change produced by ESRID is the reduction in the annual

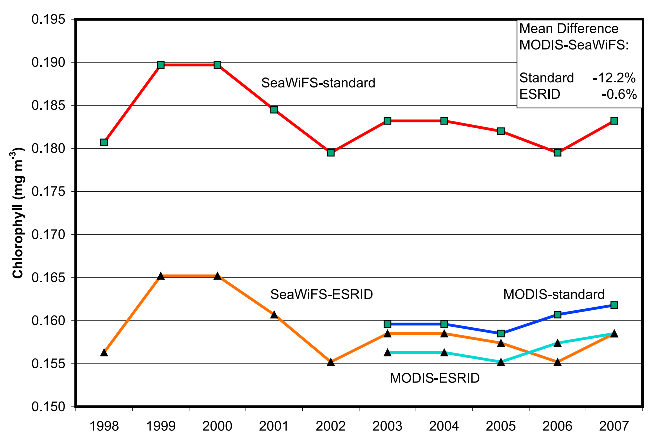

Figure 2. Global annual median chlorophyll for SeaWiFS and MODIS using the standard consistent processing method and ESRID. The mean difference between MODIS and SeaWiFS for 2003–2007 is shown.

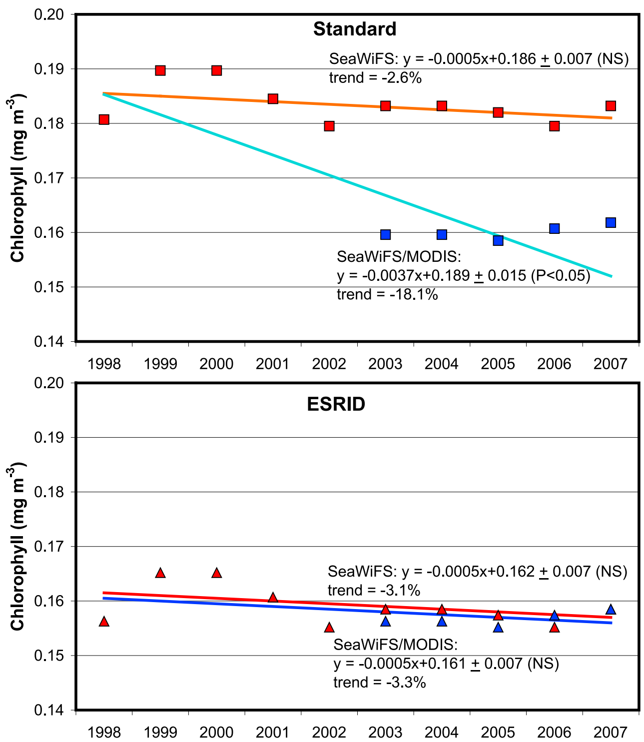

Figure 3. Regression line and error statistics for global annual median chlorophyll for the SeaWiFS record 1998–2007 and the standard SeaWiFS/MODIS combination (SeaWiFS 1998–2002; MODIS 2003–2007). (top) Standard consistent processing method. (bottom) ESRID. In parentheses the statistical significance is provided (NS indicates not significant at $P < 0.05$). y is the chlorophyll (mg m^{-3}), and x is the year minus 1997 so that year 1 is 1998. The trend represents the difference in y at year 1 and year 10, expressed as a percent.

median chlorophyll for SeaWiFS. ESRID reduces MODIS global annual medians slightly (<0.005 mg m^{-3}).

[13] These differences translate into changes in trends estimated by linear regression. For the period 1998 through 2007, global annual median SeaWiFS chlorophyll indicates a trend of −2.6% (Figure 3), which is not significant at a probability of 0.05 (95% confidence). When MODIS is substituted for SeaWiFS in 2003, the 1998–2007 trend is −18.0%, which is statistically significant ($P < 0.05$). Using ESRID, a trend of −3.3% is found and is not statistically significant.

[14] Similar large discrepancies between the annual medians of the two sensors are observed in the oceanographic basins least affected by sampling differences: ranging from −11% in the South Atlantic to −20% in the South Pacific (Figure 4). These differences improve to −1.4% and −1.0%, for the same basins, respectively, using ESRID. In fact, differences are reduced in all the oceanographic basins using ESRID. However, only modest reductions occur in the North Atlantic (−25.8% to −18.4%) and North Pacific (−21.5% to −13.2%). These two basins exhibit the smallest improvement by ESRID.

[15] The differences in regional annual median chlorophyll are larger than the maximum interannual variability observed in SeaWiFS for all 12 basins using the standard method (Figure 4). Only 4 basins exhibit differences that exceed interannual variability using ESRID. All 4 are impacted by sampling issues.

4. Discussion

[16] The differences in global annual median chlorophyll from SeaWiFS and MODIS during an overlap period 2003–2007 raise issues for using them in succession to reliably monitor long-term change related to climate. The differences are −12.2% globally (SeaWiFS higher), and range from −7.3% to −25.8% regionally. Furthermore, substituting MODIS for SeaWiFS data for the last 5 of 10 years produces a different global trend over 10 years than from SeaWiFS. These differences and trends suggest inconsistency between the two sensor data sets, despite consistency in processing methodology. The inability of sensor data sets to produce consistent, climatically useful information is not limited to the field of ocean color. It is a problem common to many satellite data sets [*Ohring et al.*, 2007].

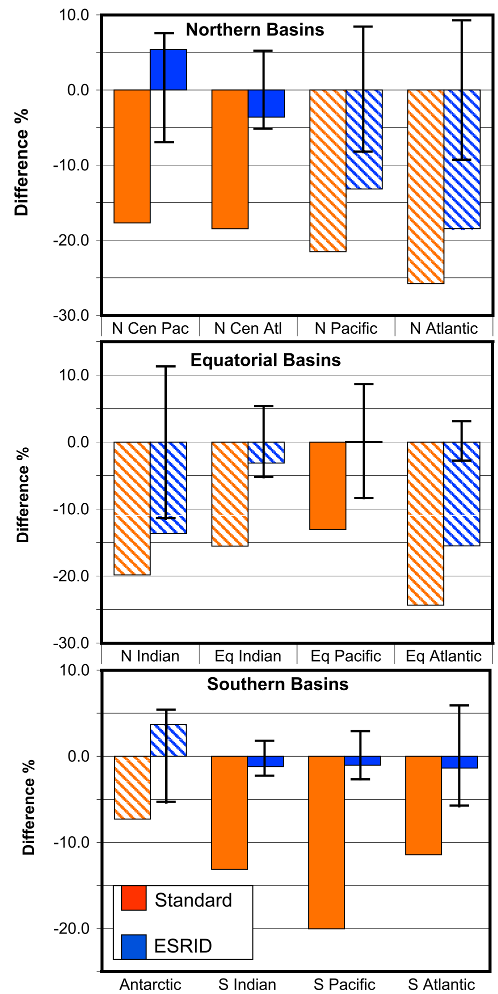

Figure 4. Mean of global annual median difference in chlorophyll between MODIS and SeaWiFS for the period 2003–2007. The "error" bars indicate the maximum interannual variability observed in the SeaWiFS record. Hatched bars indicate basins where >25% of the observations by one sensor were not observed by the other sensor for at least one month during 2003–2007, suggesting sampling bias.

[17] These results do not prove that consistent processing cannot produce consistent records of geophysical data, since there is a possibility of a unique problem associated with one or both of these mission data sets. However, the lack of consistency seen here suggests that more is needed than consistent processing to produce the reliability needed to support climate analysis over the long term (i.e., spanning >1 mission).

[18] ESRID, in contrast to standalone uniform processing, improves the consistency between SeaWiFS and MODIS chlorophyll data sets. Globally, and in oceanographic basins unaffected by sampling differences, the improvement is striking: from −12.2% to −0.6% globally, and as much as −20.0% to −1.0% in the South Pacific basin. The trend from the SeaWiFS-MODIS succession is in agreement with that from SeaWiFS alone. ESRID achieves these improvements by intimately incorporating in situ data in a post-processing analysis. The result is that ESRID minimizes biases in the ocean color data, specifically those arising from calibration, different band locations, bandwidths, sensor sensitivities, and time of observation, among others.

[19] How much consistency is needed for ocean color data to satisfy requirements for observing climate change? The National Research Council provides a qualitative definition of CDRs: "A time series of sufficient length, consistency, and continuity to determine climate variability and change" [*National Research Council*, 2004], leaving specifics up to Earth sciences disciplines. We suggest a quantitative requirement based on the expectation that the climate change (trend) signal is smaller than variability (seasonal and interannual) [*Ohring et al.*, 2007], and evaluate the interannual variability observed in the decadal ocean color record. The maximum interannual variability in the SeaWiFS record for 1998–2005 is about ±3% globally [*Gregg et al.*, 2009]. We suggest this sets the upper limit for an ocean color CDR. The standard consistent processing does not meet this threshold: at a −12% difference between the two ocean color data sets, it is about 4 times too large. ESRID, at a −0.6% difference, meets the threshold and suggests a viable alternative approach for producing CDRs.

[20] In fact, the sensor differences for the standard method do not meet the interannual variability threshold in any of the basins (Figure 4). They are often many times higher, for example >6 times in the South Atlantic and Pacific. The ESRID differences only exceed the interannual variability in 4 basins, each of which are suspected of sampling issues (Figure 4). In three of these basins, the North Atlantic, North Pacific, and North Indian, MODIS and SeaWiFS have exhibited large sampling biases [*Gregg and Casey*, 2007]. The fourth, the Equatorial Atlantic, showed sampling biases >25% over vast portions of the basin that did not appear in the annual mean. Here we find that locations observed by one sensor but not the other in this basin are often >35% of the total, and reach a maximum of 42% in Feb 2004.

[21] The results highlight the need for overlapping missions to understand the contribution of sensor/mission artifacts relative to natural variability. Had MODIS and SeaWiFS not overlapped in time, it would have been difficult, if not impossible, to know how much of the observed change was due to artifacts.

[22] SeaWiFS and MODIS not only observe chlorophyll distributions differently [*Morel et al.*, 2007] they also observe different chlorophyll distributions. Differences in sensor design and orbit, such as different band locations (MODIS has only 3 bands used for chlorophyll retrieval while SeaWiFS has 4, and some are in different spectral locations), band widths (MODIS is narrower), sensitivities (MODIS has higher digitization and signal-to-noise ratios) and viewing at different time of day (MODIS near 1330 and SeaWiFS near noon and drifting), cause each sensor to report different values of chlorophyll even at the same location. This is despite concerted attempts to equalize the processing of the two sensor data sets. These four sensor design and orbit differences each contribute to the differences in retrieved chlorophyll, the relative contributions of which change with location and time.

[23] Additionally, differences in orbit and radiance thresholds lead to the observation of different locations. These sampling differences can be caused by sun glint, sensor tilt, solar zenith angle, inter-orbit gaps, clouds, and aerosols. Of these, solar zenith angle and aerosols are responsible for most of the sampling differences between sensors. The solar zenith angle limit contributes to the differences observed in the North Atlantic and Antarctic, and partially the North Pacific. Differences in sampling due to different masking of aerosols are the primary cause of sampling issues in the Equatorial basins and partially the North Pacific. Although a thorough analysis of the inter-sensor sampling differences is beyond the scope of this paper, we estimated where such issues are likely to occur based on the fraction of the basin that is observed by one sensor but not the other, and by reference to previous estimates of sampling biases.

[24] ESRID is capable of producing consistent results globally and regionally where the problems are primarily due to the inability of SeaWiFS and MODIS to report similar chlorophyll distributions due to sensor design and observation time. It forces agreement with in situ data, creating a unified description of ocean biology among diverse observational platforms. It cannot remove differences due to sampling. Thus we see major improvements in consistency in all the basins that appear to have limited sampling issues. ESRID still improves the other basins, but the improvement is reduced since it only affects the component due to sensor design differences. Regional sampling issues are a small fraction of the global results: locations observed by one sensor but not the other are <15% as a monthly global maximum. Thus sampling issues do not substantially affect the global differences. This explains the substantial improvement in consistency produced by ESRID on a global basis.

[25] ESRID reduces inconsistencies between two sensor data sets that have been processed using consistent algorithms and calibration. How well can it perform in the absence of consistent processing? Comparing SeaWiFS data derived from the circa 2007 algorithm suite with methods from the 2002 period, we find the mean global annual median difference for 1998–2005 to be 11.8% (SeaWiFS 2002 algorithms – SeaWiFS 2007 algorithms). When we apply ESRID the global difference improves to −2.0%. Now there is much more in common with the two SeaWiFS algorithms and calibration between 2002 and 2007 than there is different. For example, atmospheric correction and the general form of the bio-optical algorithms are similar. Sampling is nearly identical. But there are major differences as well, such as algorithms to correct bi-directional reflectance and

changes in bio-optical algorithm empirical coefficients, and calibration. This suggests ESRID can give latitude to the choice of processing algorithms and still achieve consistency.

[26] The differences in sensor behavior and sampling between SeaWiFS and MODIS reported here produce representations of ocean chlorophyll that do not appear to support the consistency needed for multi-mission ocean color CDRs. Use of a new post-processing methodology (ESRID) that essentially forces satellite data to agree with in situ data improves the consistency of two missions enough that the differences are less than the maximum observed interannual variability globally and in many oceanographic basins. This improved consistency is a step toward the development of long-term ocean color CDRs across multiple missions.

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References

Aiken, J., et al. (2000), The Atlantic Meridional Transect: Overview and synthesis of data, *Prog. Oceanogr.*, *45*, 257–312, doi:10.1016/S0079-6611(00)00005-7.

Antoine, D., A. Morel, H. R. Gordon, V. F. Banzon, and R. H. Evans (2005), Bridging ocean color observations of the 1980s and 2000s in search of long-term trends, *J. Geophys. Res.*, *110*, C06009, doi:10.1029/2004JC002620.

Behrenfeld, M. J., et al. (2006), Climate-driven trends in contemporary ocean productivity, *Nature*, *444*, 752–755, doi:10.1038/nature05317.

Conkright, M. E., et al. (2002), *World Ocean Database 2001*, vol. 1, *Introduction*, *NOAA Atlas NESDIS*, vol. 42, edited by S. Levitus, 167 pp., NOAA, Silver Spring, Md.

Gregg, W. W., and N. W. Casey (2007), Sampling biases in MODIS and SeaWiFS ocean chlorophyll data, *Remote Sens. Environ.*, *111*, 25–35, doi:10.1016/j.rse.2007.03.008.

Gregg, W. W., and M. E. Conkright (2002), Decadal changes in global ocean chlorophyll, *Geophys. Res. Lett.*, *29*(15), 1730, doi:10.1029/2002GL014689.

Gregg, W. W., M. E. Conkright, P. Ginoux, J. E. O'Reilly, and N. W. Casey (2003), Ocean primary production and climate: Global decadal changes, *Geophys. Res. Lett.*, *30*(15), 1809, doi:10.1029/2003GL016889.

Gregg, W. W., N. W. Casey, and C. R. McClain (2005), Recent trends in global ocean chlorophyll, *Geophys. Res. Lett.*, *32*, L03606, doi:10.1029/2004GL021808.

Gregg, W. W., N. W. Casey, J. E. O'Reilly, and W. E. Esaias (2009), An empirical approach to ocean color data: Reducing bias and the need for post-launch radiometric re-calibration, *Remote Sens. Environ.*, *113*, 1598–1612, doi:10.1016/j.rse.2009.03.005.

Kahru, M., and B. G. Mitchell (2008), Ocean color reveals increased blooms in various parts of the world, *Eos Trans. AGU*, *89*(18), doi:10.1029/2008EO180002.

McClain, C. R., S. R. Signorini, and J. R. Christian (2004), Subtropical gyre variability observed by ocean-color satellites, *Deep Sea Res., Part II*, *51*, 281–301, doi:10.1016/j.dsr2.2003.08.002.

Morel, A., et al. (2007), Examining the consistency of products derived from various ocean color sensors in open ocean (case 1) waters in the perspective of a multi-sensor approach, *Remote Sens. Environ.*, *111*, 69–88, doi:10.1016/j.rse.2007.03.012.

National Research Council (2004), *Climate Data Records From Environmental Satellites*, 136 pp., Natl. Acad. Press, Washington, D. C.

Ohring, G., et al. (2007), Achieving satellite instrument calibration for climate change, *Eos Trans. AGU*, *88*(11), doi:10.1029/2007EO110015.

Polovina, J. J., E. A. Howell, and M. Abecassis (2008), Ocean's least productive waters are expanding, *Geophys. Res. Lett.*, *35*, L03618, doi:10.1029/2007GL031745.

Werdell, P. J., and S. W. Bailey (2005), An improved in-situ bio-optical data set for ocean color algorithm development and satellite data product validation, *Remote Sens. Environ.*, *98*, 122–140, doi:10.1016/j.rse.2005.07.001.

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