# MODIS/Aqua Ocean Reprocessing 1

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## Introduction

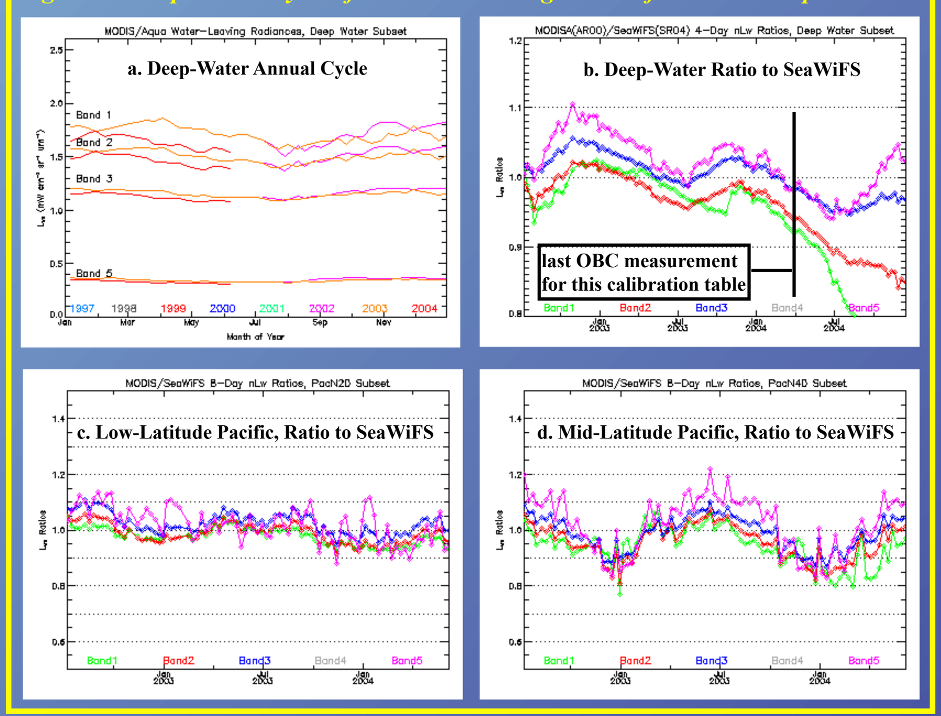
The Ocean Biology Processing Group (OBPG) has recently completed a reprocessing of the ocean products derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) currently flying on the Aqua spacecraft. The reprocessing includes updates to the instrument calibration, as well as revisions to the atmospheric correction algorithm and tables, corrections for bidirectional reflectance of water-leaving radiances, and additional masking to remove straylight contamination. Each proposed change was evaluated incrementally, using a comprehensive set of analyses (Franz et al., 2005) to evaluate the impact of the change on global spatial scales and life-of-mission time scales. This presentation will briefly discuss the issues prior to reprocessing, describe the changes adopted, and show some results from MODIS/Aqua Ocean Reprocessing 1.

## I. Remaining Issues After Initial OBPG Processing

The initial OBPG processing of MODIS/Aqua was completed in April of 2004, and the same calibration and processing configuration was maintained for forward processing through February of 2005. While this initial processing addressed a number of significant errors relative to previously distributed versions of MODIS/Aqua ocean products (e.g., Meister et al., 2005), some remaining issues and unexplained inconsistencies between MODIS and SeaWiFS products were still evident. These included:

1) Inconsistency in the annual cycle of global water-leaving radiances (Figure 1a)
2) Long-term change and seasonal deviations relative to SeaWiFS global trends (Figure 1b)
3) Differences relative to SeaWiFS which increase with latitude or solar zenith angle (Figure 1c, 1d)
4) Large differences relative to SeaWiFS in global mean aerosol optical thickness

Figure 1: *Temporal Analysis of Initial Processing Results for MODIS/Aqua Oceans*




## II. Changes for Reprocessing 1

The deep-water trends shown in Figure 1b illustrate the most immediate issue: severe degradation in relative agreement with SeaWiFS, especially by mid-2004. This problem is simply due to an out-dated instrument calibration. The temporal calibration of MODIS/Aqua is derived from trends in the solar diffuser (SD) measurements, augmented by lunar observations which determine change in response versus scan-angle (RVS). These Onboard Calibrator (OBC) measurements are used by the MODIS Calibration Support Team (MCST) to derive the calibration look-up table (LUT). The LUT in use for the initial reprocessing (MCST V4.3.1.5s) was based on OBC measurements through March of 2004, and the instrument response was deviating significantly from the extrapolated trends.

### II.1. Updated Instrument Calibration

The LUT employed for this reprocessing is based on MCST LUT V5.0.1, which incorporates OBC measurements through November 2004. The OBPG modified this LUT based on further analysis of the SD measurements, which have revealed a significant correlation between the variation in Sun beta-angle (yaw angle) on the diffuser and periodicities observed in the solar-diffuser gains. The effects are band and detector dependent, and the evidence suggest that the likely cause is uncorrected vignetting of the diffuser screen (which is only used for the ocean bands, to prevent saturation). For more details see Meister, 2004. The OBPG removed this effect from the diffuser trends by statistical correlation, and refit the corrected diffuser trends to a simple exponential function to derive the new LUT used for the reflective solar bands. The differences between the MCST approach and the new approach are relatively small for those periods of time where calibration measurements are available (in this case, up to November 2004), but large differences can occur for the extrapolation of the calibration into the future. It is believed that this modified LUT will better predict the future response of the instrument, assuming degradation remains well behaved, and thus reduce the need for frequent calibration LUT updates.

Figure 2 shows the deep-water nLw trend ratio to SeaWiFS, after the updated LUT has been applied to MODIS/Aqua, but before other reprocessing changes. Comparing this to Figure 1b, it can be seen that the new MODIS LUT significantly improves agreement with SeaWiFS over the Aqua mission lifespan.

Figure 2
*Deep-Water nLw Ratio to SeaWiFS*

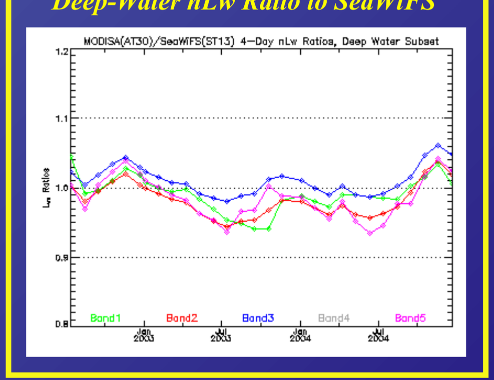


Table 1: *Sensor Bands (nm)*

| Band | SeaWiFS | MODIS |
|---|---|---|
| 1 | 412 | 412 |
| 2 | 443 | 443 |
| 3 | 490 | 488 |
| 4 | 510 | 531 * |
| 5 | 555 | 551 |

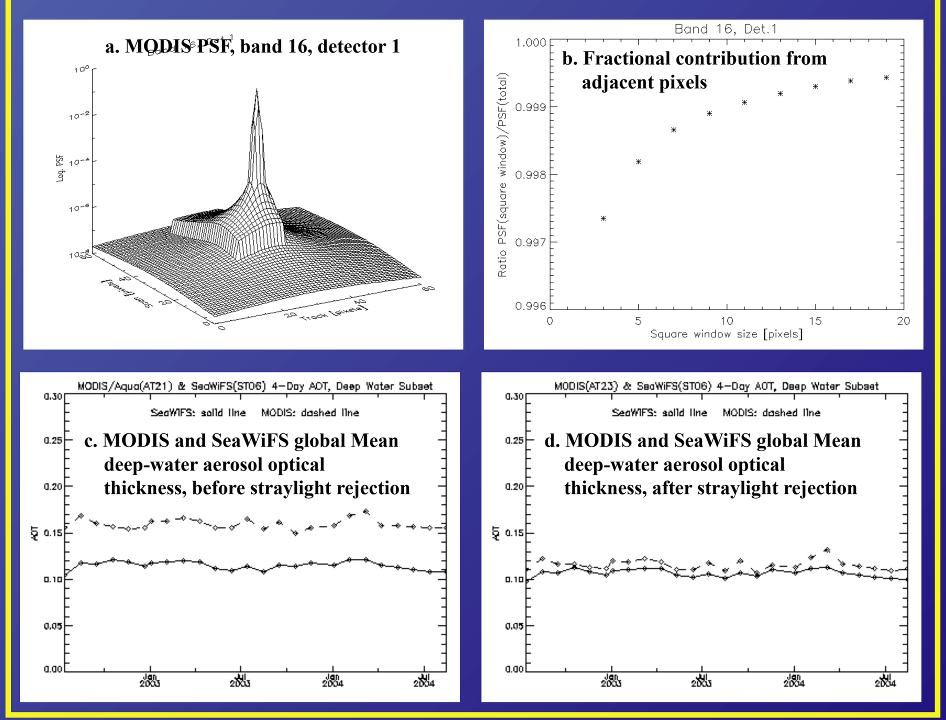
** not compared*

### II.2. Removal of Straylight Contamination

The straylight of an instrument is characterized by its Point Spread Function (PSF). The PSF of MODIS/Aqua was not measured prelaunch. The OBPG has developed a model of the PSF based on the Line Spread Function (LSF), for which measurements were taken in the scan direction. Figure 3a shows the modeled PSF for band 16 (869 nm), detector 1. The shape of the PSF is strongly influenced by the position of the detector on the focal plane. The central pixel typically measures only 66% of the correct intensity. As shown in Figure 3b, a 3x3 window around the central pixel captures about 0.9973% of the intensity and a 5x5 window captures about 0.9982%. The MODIS PSF will result significant straylight contamination from adjacent pixels. The largest impact is to low radiance ocean observations which are within a few kilometers of bright sources such as clouds, coastlines, or sun glitter. Until a correction can be developed, the near-term solution is to simply mask all observations within a few pixels of any cloud or saturation-flagged pixels. The model estimates of the point-spread function for MODIS suggest that the majority of the contamination can be eliminated with a 7x5-pixel masking (+/-3 pixels along scan, +/-2 pixels along track) around these high-radiance pixels. This represents a considerable data loss at Level-2, but confidence in the remaining data is substantially enhanced.

A direct impact of this additional masking can be seen in the global deep-water aerosol optical thickness (AOT) comparisons with SeaWiFS. The straylight masking brings MODIS mean AOT retrievals down by more than 50%, and the results are now in good agreement with SeaWiFS. Note that the standard SeaWiFS processing already includes masking and correction for straylight contamination.

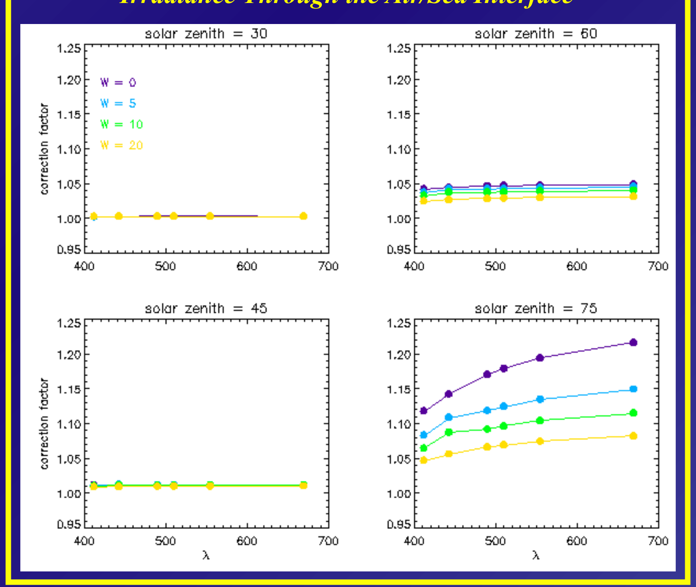
Figure 3: *Analysis and Removal of Straylight Contamination*




### II.3. Reflection/Refraction Correction for Downwelling Irradiance

The exact normalization of water-leaving radiances (nLw) requires consideration of the reflection and refraction of photons as they interact with and cross the air-sea interface (Mobley 1994, Morel et al. 2002). The initial MODIS processing included a spectrally-independent Fresnel-based correction to account for subsurface upwelling radiance propagating upward through a flat sea surface (Franz et al. 2000). For the reprocessing, an additional Fresnel correction was developed (M. Wang) to account for surface irradiance propagating downward through a wind-roughened sea surface. This spectrally-dependent correction depends both on the solar zenith angle and wind speed (indicated as W in unit of m/s in Figure 4). The spectral dependency stems from the atmospheric (aerosol) conditions considered in the model derivation. The additional correction applied in this reprocessing is minimal at low solar zenith angles. It becomes significant above 50 degrees, reaching ~5% at 60 degrees and 10-20% at 75 degrees solar zenith (highest at longest wavelengths). The correction also accounts for changes in sea surface conditions, as the downwelling reflection/refraction losses diminish with increasing wind speed (surface roughness).

Figure 4: *Reflection/Refraction Correction for Downwelling Irradiance Through the Air/Sea Interface*

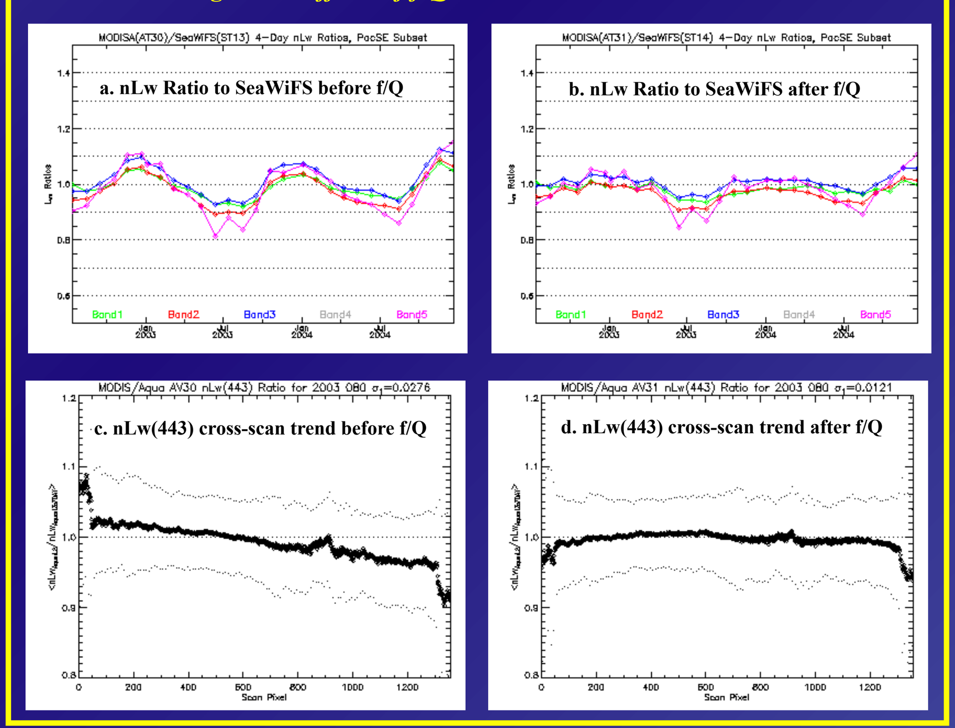



### II.4. Normalization for Nonisotropic Subsurface Light Field (f/Q)

The exact normalization of water-leaving radiances also requires consideration of the bidirectional properties of the subsurface light field (Morel et al. 1996, 2002). The f/Q correction developed by Morel et al. accounts for the spectrally-dependent, non-isotropic structure of the upwelling radiance. The f/Q correction depends on sensor and solar zenith angles, their relative azimuth angle, and in-water constituents. With regards to the latter, Case-1 conditions are implied and the chlorophyll concentration is used to approximate the marine inherent optical properties (e.g., the volume scattering function). Please refer to Morel et al. 2002 (and references therein) and the OBPG BRDF Evaluation Web page for additional details and analyses.

Some benefits of applying the f/Q correction include reduction of mid-latitude seasonal differences between MODIS/Aqua and SeaWiFS, and reduction of significant cross-scan trends in the MODIS water-leaving radiances. Figure 5a shows the ratio of MODIS/Aqua to SeaWiFS for a region of the south-east Pacific, where seasonal differences between the two sensors are very clear. Figure 5b shows the same region after f/Q correction was applied to both sensors, and sensor to sensor agreement is much improved. Similarly, Figure 5c shows residual cross-scan trends in MODIS/Aqua nLw before application of the f/Q correction, as derived by normalization of Level-2 images to Level-3 means (Franz et al., 2005). Figure 5d shows the same analysis after application of the f/Q correction, where the resulting cross-scan trend is much reduced. This improved cross-scan stability has been seen across visible wavelengths and over the mission lifespan.

Figure 5: *Effects of f/Q Correction on retrieved nLw*




### II.5. Other Changes

**Updated relative spectral response (RSR) functions:** The RSRs were revised to better integrate the measured inband and out-of-band components. Relevant quantities were recomputed, including Rayleigh reflectance tables, solar irradiances, and out-of-band corrections. After vicarious calibration, the impact of these changes was minor.

**Enhanced Rayleigh pressure correction:** The pressure correction was expanded by M. Wang to include effects along the solar path. The impact of this change is generally small, but can exceed 5% of water-leaving radiances at high solar zenith angles, if pressure deviates significantly from standard sea-level conditions.

**Reduced solar zenith threshold:** Previous processing by OBPG of MODIS and SeaWiFS products limited the solar zenith to 75 degrees through Level-3 masking. The solar zenith limit has been reduced to 70 degrees to reflect current confidence in atmospheric correction and polarization correction algorithms at extreme path geometries.

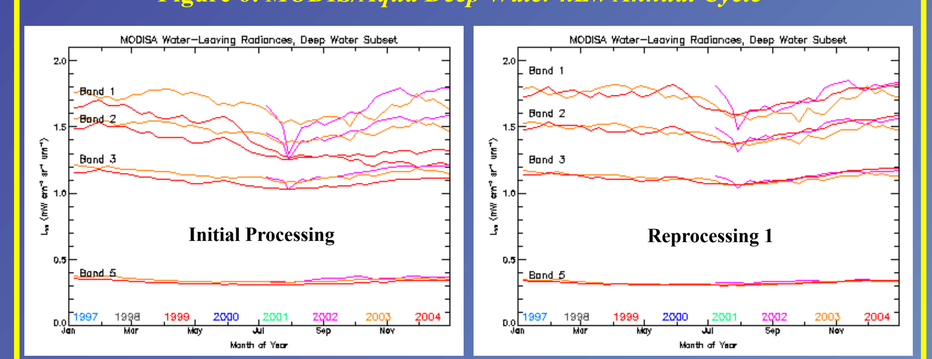
**Updated vicarious calibration:** The vicarious calibration of MODIS/Aqua to the Marine Optical Buoy (MOBY) is updated whenever instrument calibration or processing algorithms are changed. The final vicarious calibration for this reprocessing also includes a revised set of MOBY measurements, which follow a recent MOBY reprocessing by NOAA.

## III. Reprocessing Results

On average, the changes made for this reprocessing will tend to lower chlorophyll retrievals by 5-15%, with the least change in clear waters and the largest change in coastal waters. This is within the noise of *in situ* comparisons, but the mean ratio of MODIS to *in situ* chlorophyll is improved, from 10% high before reprocessing to 4% low after reprocessing.

It was already shown in Figure 5d that cross-scan stability has been improved through application of the f/Q correction. Improvement in temporal stability is demonstrated by Figure 6, which shows the annual trend in MODIS/Aqua deep-water mean nLw, before and after reprocessing. In the absence of any major geophysical events, it is expected that this seasonal cycle will roughly repeat from year to year. The annual repeatability is much improved with Reprocessing 1, primarily due to the updated instrument calibration.

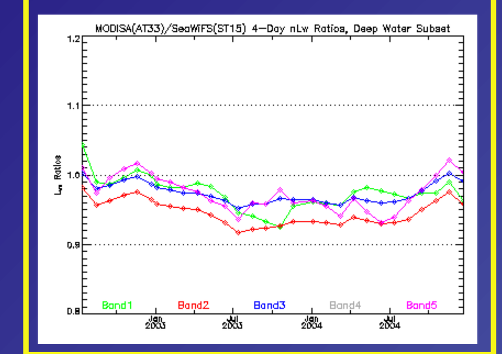
Figure 6: *MODIS/Aqua Deep-Water nLw Annual Cycle*




## Reprocessing Results (continued)

Direct comparison of the MODIS/Aqua Reprocessing 1 result to SeaWiFS is Shown in Figure 1. For this analysis, the SeaWiFS data set was reprocessed to include all relevant processing changes, including f/Q and expanded reflection/refraction corrections, enhanced Rayleigh pressure corrections, and updated MOBY calibration (the full reprocessing of SeaWiFS is pending). The results in Figure 7 show much improved agreement between the two sensors, as compared to Figure 1b, with mean differences in at-surface radiances of order 5%. The best agreement occurs at the beginning and end of the Aqua mission, with the mid-mission period biased low in MODIS. This may be an indication of residual (0.5%) error in the instrument temporal calibration. Further analysis of the solar and lunar OBC data is continuing.

Figure 7: MODIS/Aqua *Deep-Water nLw Ratio to SeaWiFS*



It was shown in Figure 5a and 5b that the application of the f/Q correction reduces the seasonal differences previously observed between MODIS and SeaWiFS at middle to high latitudes (higher solar zenith angles). This is further illustrated in Figure 8, which shows MODIS nLw ratios to SeaWiFS at various latitudinal zones in the northern Pacific, before and after reprocessing. The agreement is still imperfect, but it is much improved.

Figure 8: *MODIS/Aqua nLw Ratios to SeaWiFS, Before and After Reprocessing Changes*

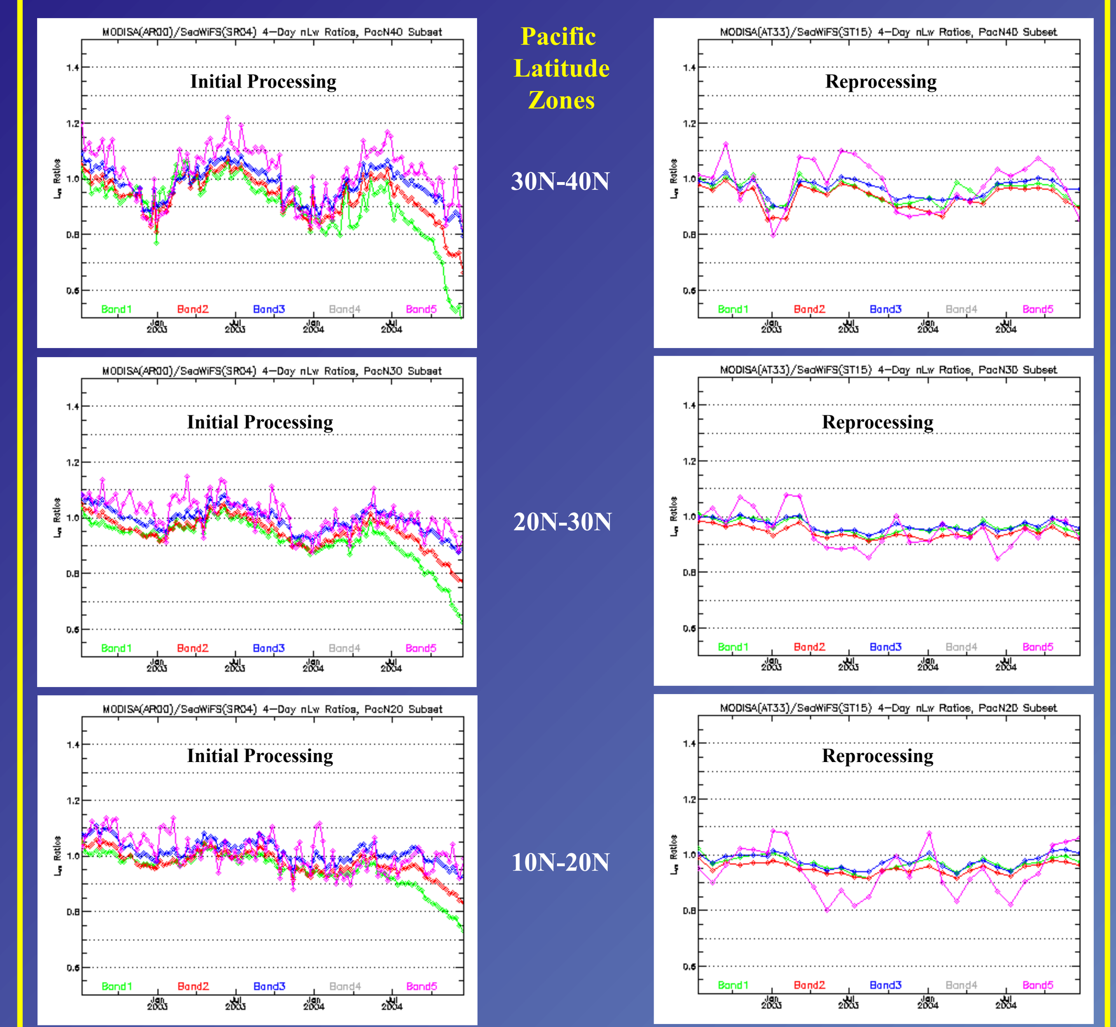



Table 2 presents global and temporally mission averaged comparisons for MODIS/Aqua and SeaWiFS chlorophyll and water-leaving radiances, for clear, deep, and coastal waters (Franz et al., 2005). These numbers were computed by averaging the 4-day global means over the lifetime of the Aqua mission. The standard deviation is therefore a measure of observed seasonal variability. The two sensors show very good agreement, on average, in clear and deep waters, with chlorophyll and radiances in agreement to within 5%. Temporal variability in the retrieved ocean color products is also quite comparable. Larger difference is seen in the coastal chlorophyll retrievals, but this is in part due to the difference in chlorophyll algorithms employed, and specifically the lack of a 510nm band on MODIS.

Table 2: *Mean and Standard Deviation of the Global Trends*

| | | chlorophyll | | nLw_412 | | nLw_443 | | nLw_490 | | nLw_555 | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Sensor | Subset | mean | stdev | mean | stdev | mean | stdev | mean | stdev | mean | stdev |
| SeaWiFS | Clear | 0.078 | 0.0035 | 2.191 | 0.0702 | 1.861 | 0.0505 | 1.261 | 0.0188 | 0.297 | 0.0043 |
| MODIS | Clear | 0.074 | 0.0032 | 2.156 | 0.0697 | 1.787 | 0.0539 | 1.250 | 0.0228 | 0.298 | 0.0064 |
| SeaWiFS | Deep | 0.171 | 0.0150 | 1.772 | 0.0534 | 1.561 | 0.0383 | 1.146 | 0.0187 | 0.329 | 0.0053 |
| MODIS | Deep | 0.175 | 0.0209 | 1.728 | 0.0680 | 1.476 | 0.0468 | 1.116 | 0.0250 | 0.321 | 0.0090 |
| SeaWiFS | Coastal | 0.935 | 0.1519 | 0.792 | 0.054 | 0.884 | 0.0436 | 0.885 | 0.0389 | 0.457 | 0.0268 |
| MODIS | Coastal | 1.167 | 0.1933 | 0.754 | 0.017 | 0.814 | 0.0501 | 0.848 | 0.0433 | 0.446 | 0.0288 |

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