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Monitoring Bio-Optical Processes Using NPP-VIIRS And MODIS-Aqua Ocean Color Products

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ABSTRACT

Same day ocean color products from the S-NPP and MODIS provide for a new capability to monitor changes in the bio-optical processes occurring in coastal waters. The combined use of multiple looks per day from several sensors can be used to follow the water mass changes of bio-optical properties. Observing the dynamic changes in coastal waters in response to tides, re-suspension and river plume dispersion, requires sequential ocean products per day to resolve bio-optical processes. We examine how these changes in bio-optical properties can be monitored using the NPP and MODIS ocean color products. Additionally, when linked to ocean circulation, we examine the changes resulting from current advection compared to bio-optical processes. The inter-comparison of NPP and MODIS ocean products are in agreement so that diurnal changes surface bio-optical processes can be characterized.

Keywords: *Ocean Color, VIIRS, satellite chlorophyll, bio-optical processes.*

1. INTRODUCTION

Coastal processes can change on hourly time scales, which can have an impact on satellite ocean color bio-optical products. The ocean color products that are produced from Moderate Resolution Imaging Spectroradiometer (MODIS) AQUA and Suomi National Polar-orbiting Partnership (S-NPP) Visible Infrared Imaging Radiometer Suite (VIIRS) satellites typically come once per day at approximately 13:00 local time and represent "one" instant view of the coastal ocean. In many instances, this view of the bio-optical properties can change throughout the day in response to changes in water color resulting from tidal fluxes, diurnal biological growth and decay, re-suspension processes and current dispersion. Changes in ocean color have been observed as a response of vertical movement of subsurface layers within first optical depth, which is sensed by satellites[1]. The ability to monitor these short temporal changes in bio-optical properties is quite difficult since it requires using multiple satellite overpasses. Furthermore, because changes in the bio-optical properties could be quite subtle, strict criteria with inter-satellite cross-calibration, identical processing codes, and algorithms must be properly used in order to monitor these short temporal bio-optical changes.

Coastal ecosystems can be monitored using ocean color products that include surface chlorophyll, euphotic depth, and inherent optical properties (IOP). The IOPs depend on the composition, morphology, and concentration of the particulate and dissolved substances in the ocean[2]. Composition refers to what materials constitute the particle or dissolved substance [colored dissolved organic matter (CDOM), non-phytoplankton organic particles (detritus)]. Morphology refers to the sizes and shapes of particles (phytoplankton, inorganic particles and bubbles). Concentration refers to the number of particles in a given volume of water, which is described by the particle size distribution. The ocean color processing for these products must to account for atmospheric correction, sensor characteristics, and calibration[3]. Atmospheric correction accounts for approximately 90% of satellite radiance and must be removed accurately by including angular effects of the sensor from the solar zenith and azimuth. Inaccuracy in properly accounting for these affects results in uncertainty in the retrieved ocean color products. Characterizing this uncertainty evaluation is essential when comparing ocean color products from different satellites i.e. MODIS-Aqua and VIIRS.

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In using sequential satellite images for monitoring daily diurnal bio-optical properties, there are three main possible processes and explanations that affect changes in the ocean color product. Specifically they are:

1**) Advection of water masses**: the movement of water masses resulting from ocean currents or tides can result in a change in bio optical properties. In our coastal Gulf of Mexico region, the movement of the river plume front and the water color changes on hourly scales can be observed in sequential images;

2) Bio-optical processes: in coastal and open waters, water color can change due to phytoplankton bloom or decay. Furthermore, the subsurface phytoplankton and optical layers can change depth with the first optical depth and impact ocean color sensed in sequential satellite images. In addition, re-suspension of particles from physical mixing can increase optical backscattering in the ocean color product; and

3) Satellite sensor characteristics and processing: the differences in sequential satellite products can result from inaccuracies in satellite processing. For example, atmospheric correction requires precise removal of Rayleigh and aerosol scattering which must account for satellite sensor and solar zenith angles. Additionally, the Bidirectional Reflectance Distribution Function (BRDF) of the water particles is similarly dependent on satellite and solar zenith and azimuth angles[4]. The influence of BRDF is more pronounced in a high scattering environment such as particle rich coastal waters than in chlorophyll dominant (case 1) water types. Differences between satellite sensors such as channel bandwidth, out of band response, and absolute calibration will also result in product differences. By using the same sensor for collecting sequential images, we eliminate some product uncertainty associated with using different sensors. However, specific sensor design characteristics must be correctly taken into consideration. For example, in the NPP–VIIRS sensor the characteristics of the Half Angle Mirror (HAM) of the sensor mirror impacts the extreme left and right sides of the scan [5].

By examining multiple looks per day using MODIS and VIIRS satellite bio-optical products, short temporal coastal processes can be characterized. However, because these are different satellites, the product uncertainty can result from sensor characteristics instead of coastal processes. Ideally, the same sensor should be used to monitor temporal changes in coastal bio-optical processes. This is an attractive feature of geostationary satellites such as Geostationary Ocean Color Imager (GOCI). The VIIRS orbit provides an overlap of the sensor swath width so that multiple looks per day and bio-optical products can be collected over the same ocean. At a 30-degree latitude, the overlap is approximately 700 km with an approximate 100 minute time delay. This orbital overlap occurs approximately every two days based on VIIRS orbital progression. Therefore, using the VIIRS sensor regional overlap provides a method to observe about 100 minute changes in bio-optical coastal processes with the advantage of using the same sensor with accurate processing and sensor characteristics. Ocean color processing must account for the accurate removal of angular dependence of the spectral Rayleigh scattering ($Lr\lambda$) and aerosol scattering ($La\lambda$). The aerosol contribution is dependent on correct selection of the aerosol type and epsilon [2,6]. In order to examine sequential images to assess bio-optical changes, we must first establish the level of uncertainty that can result from ocean color processing.

The objective of this paper is to track rapid changes in the bio-optical properties of the near coast by using multiple looks from two VIIRS overlaps and one MODIS satellite. Temporal changes in the retrieved ocean color (normalized water leaving radiance - nLw) and the bio-optical products (chlorophyll) will be addressed to examine the impact of sensor specific characteristics and bio-optical responses on the retrieved chlorophyll products. The hourly changes in coastal locations of specific features and the changes in the bio-optical processes will be determined. Understanding these spatial and temporal correlation scales is important so that we can better define product uncertainty. Furthermore, these spatial and temporal scales are important to define for performing ocean color product validation which is based on matching *in situ* and satellite products. Understanding uncertainty in bio-optical products within a 100-minute period will help determine the confidence of satellite products to be used for *in situ* matchup statistics.

2. SATELLITE SENSORS AND ORBITAL OVERLAP

The Joint Polar Satellite System (JPSS) launched the S-NPP satellite including the VIIRS on October 28, 2011. This particular instrument has the capability to monitor ocean color properties [7]. The VIIRS sensor has five spectral channels centered at 412, 445, 488, 555 and 672 nm that are used to characterize spectral ocean color. The MODIS Aqua satellite has similar multispectral channels for deriving ocean color products. The processing software used to produce the ocean color products was derived from the Navy APS's software. APS is a similar version of l2gen used by NASA Ocean Biology Processing Group (OBPG). The VIIRS Sensor Data Record (SDR) data was drawn from Interface Data Processing System (IDPS) while MODIS Aqua Level 1 was from NASA (http://oceancolor.gsfc.nasa.gov/). Both satellites have a local equatorial crossing time that is approximately 1:30 p.m. in an ascending node in a sunsynchronous, near-polar, circular orbit. The swath of S-NPP is 3200 pixels from ± 70 degrees, with a 742m spatial resolution, which results in a spatial overlap with increasing latitudes. As shown in Figure 1, in the Gulf of Mexico (30-degree latitude), the overlap between VIIRS sequential orbits is 101 minutes and MODIS Aqua is in between. The yellow box shows the overlap region for the VIIRS sensor of approximately 700 pixels.

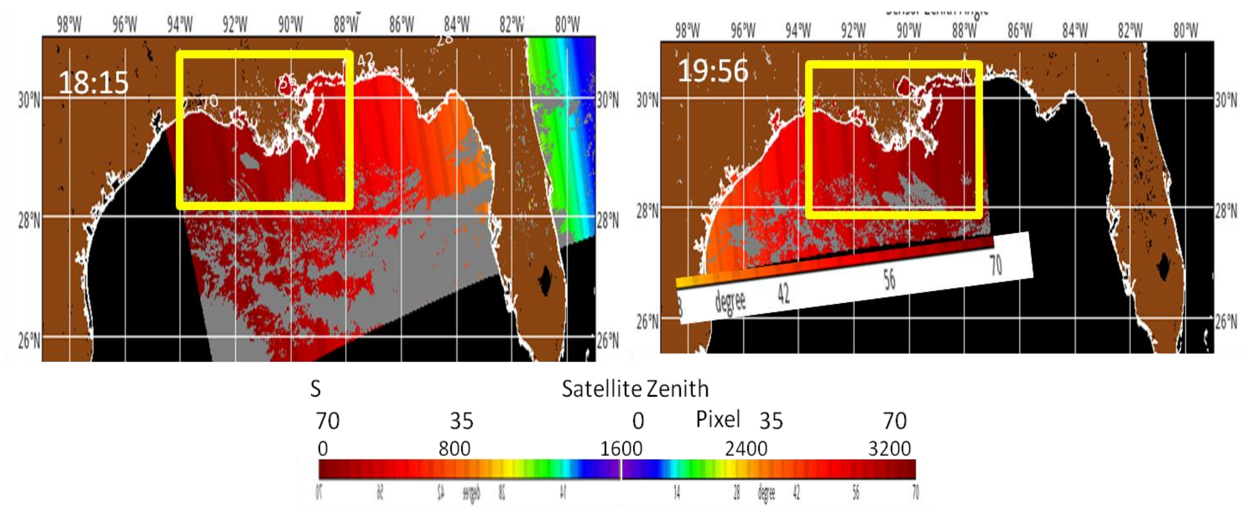

Figure 1. Overlap of the S-NPP orbit coverage in Gulf of Mexico November1 2012. The left side of scan is at 18:15 and right side scan is 19:55 GMT . The satellite zenith angles from + to - 70 degrees. MODIS pass was at 18:45 GMT.

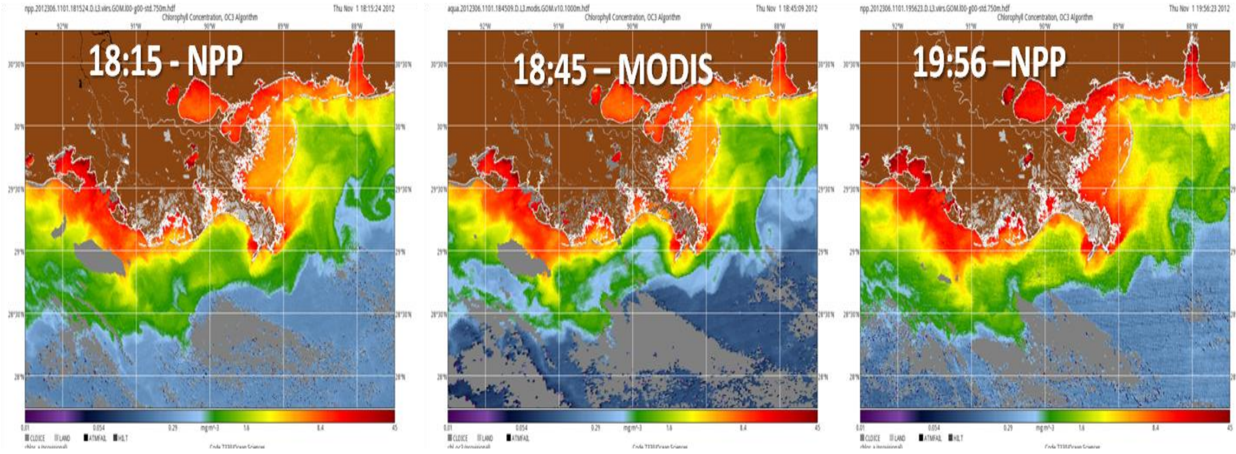

Figure 2. Chlorophyll products within 101 minutes from VIIRS and MODIS for Mississippi delta. Note the non-linear chlorophyll scale and cloud movement.

3. SEQUENTIAL IMAGERY IN THE GULF OF MEXICO

Sequential chlorophyll products from November 1, 2012 at 18:15 (VIIRS), 18:45 (AQUA) and 19:56 (VIIRS) GMT are shown in Figure 2**.** Note that the differences are greater between MODIS-Aqua and S-NPP VIIRS especially in lower chlorophyll concentrations (blue color in Figure 2). The chlorophyll algorithm (OC3) is derived from a ratio of nLw channels of 445nm: 555 and 488nm :555 nm [8].

We will further explore these differences by examining the nLw channels, which can be accomplished by selecting transect Line 2 through the sequential overlap times (Figure 3). The east-west Line 2 (Figure 3) was selected to show large variations in: a) sensor zenith angles 68^0 to 35^0; and b) different chlorophyll and nLw water masses from clear to turbid in an east to west progression. An additional reason for its selection is due to the fact that it transects the Aerosol

Robotic Network Ocean Color (AERONET-OC) Wave_CIS site. The Wave_CIS site is a part of the calibrated NASA SeaPrism sites that collect spectral water leaving radiance and aerosol radiance [9] according to specific protocols at about 30 minute intervals. The satellite retrieved normalized water leaving radiances under the transect line between orbits at 18:15, 18:45 and 19:55 GMT for the 443 and 551 channels, and corresponding sensor zenith angles, is shown in Figure 4 a,b,c for S-NPP and MODIS. Note the location of the southwest pass of the Mississippi river outlet (elevated values) and missing values at 18:15 on the west part of the transect that resulting from clouds. The nLw 551 (4b) shows close agreement between the overlap sequence, whereas the nLw 443nm (4a) shows temporal differences in the orbital sequence. The nLw 443 shows that the 18:15 (black) left side of the scan has a lower bias, while the MODIS 18:45 (red) has a high bias. There does not appear to be a trend associated with the sensor zenith (4c) as will be shown later. Notice at the AERONET-SeaPrism site located at -90.5 ^{0} longitude, the sensor zenith for the two S-NPP sequences is the same (about 63^0) and the difference in nLw 443nm is 0.4 to 0.6 µW/cm^2/nm/sr. Because the zenith angles are the same in this instance, differences may can result from changes in the ocean color within 101 minutes or because of the differences between the left and right side of the swath (i.e HAM). We compared these values to the nLw from AERONET at Wave_CIS which had measurements at 18:19, 18:57 and 19:19 GMT also shown in Figure 4 a,b (in red).The Wave_CIS values were stable for these times and had a mean nLw of at 443nm and 551nm, with values of 0.4532 and 0.4804, respectively with about 1.5% percent difference in time. The SeaPrism values are shown in Figure 4a,b as a red point:

Table 1: AERONET nLw (λ) (µw/cm2/nm) for the 4 ocean color channels for a given times in GMT.

Time GMT	411.70	442.1	551.5	668.1
18:19	0.329616	0.455242	0.485464	0.064763
18:57	0.322797	0.452281	0.484858	0.063978
19:19	0.311383	0.45218	0.47156	0.069706

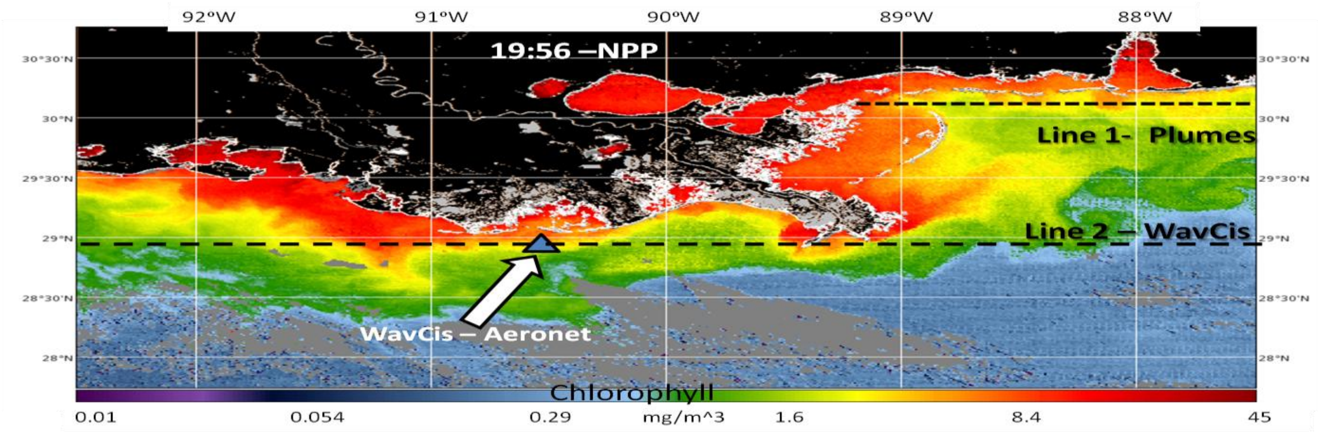

Figure 3. Location of east west transect (Line 2) which crosses the AREONET Wave_CIS Site. Clear waters in the east crossing the southwest pass of Mississippi river discharge.

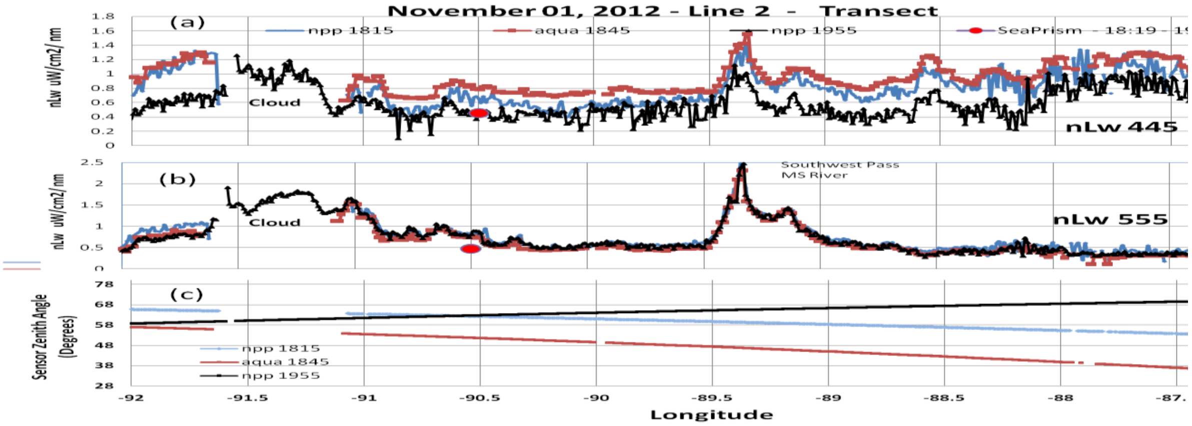

Figure 4. Transect line 2: a,b, showing the difference in nLw 445 and 555 , between sequential overlaps of NPP-VIIRS (black and blue) and MODIS (red); c) Shows the sensor zenith angle across transect. Note angle at AERONET site are both 63 degrees for NPP orbits.

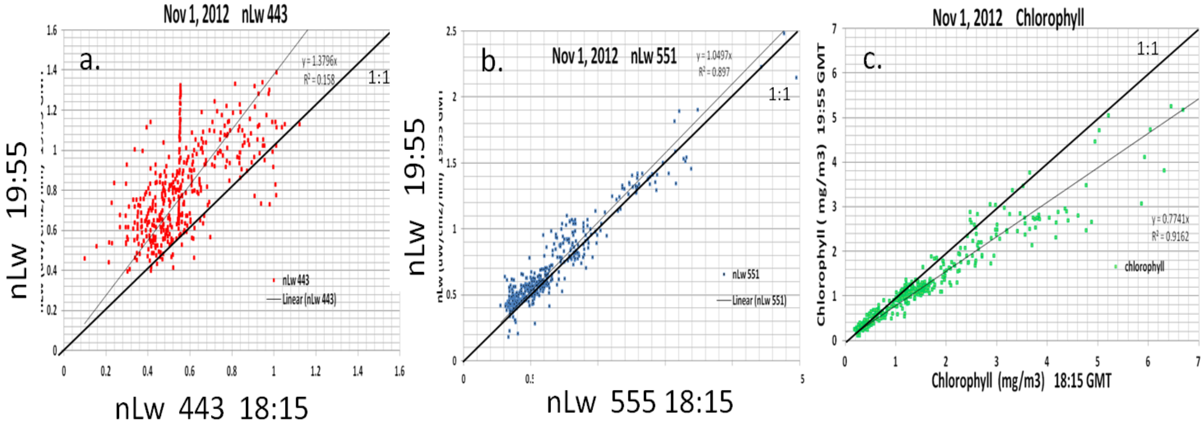

Figure 5. Differences are shown in scatterplot of a)nLw 445 b) nLw 555 and c) Chlorophyll along the transect between 18:15 and 19:55 GMT orbits.

We examined how the temporally different orbits for S-NPP impacted the nLw radiance levels and the chlorophyll concentration using scatter plots (Figure 5 a,b,c). For example, there are retrieved chlorophyll differences within the 101 minute sequence that are higher in the turbid or open ocean waters. The comparison of nLw for at 555nm for the S-NPP for 18:15 and 19:56 GMT orbits (Figure 5b) shows similar radiance values throughout the ranges (high to low) across the transect line and follows along the 1:1 line. The nLw 445nm radiances (Figure 5*a*) is scattered and shows consistently higher values in the 19:55 orbit. The resulting chlorophyll product (Figure 5*c*) shows similar values for low chlorophyll values (0-1.5 mg/m3) for both the 18:15 and 19:55 overlap period. However, in higher chlorophyll ranges (>2mg/m3) the earlier orbit (18:15) had higher chlorophyll values that result from the increased nLw at 445nm and 488nm. The difference in the retrieved satellite values from these two orbits suggests uncertainty in coastal products. This uncertainty results from both satellite processing and the natural variability in the water masses, and is critical to validating satellite products. In calibration validation analyses where the matchup statistics are performed, the spatial and temporal uncertainty of both *in situ* and satellite products are required. The differences shown along the transect provide an initial estimate that the level of uncertainty of the blue nLw 445nm is higher than the 555nm channel.

4. SATELLITE PROCESSING

Unfortunately, these differences in products using S-NPP can only be examined using the overlap areas where there are high sensor angles, which precludes the sides of the scan and the sensor nadir. We examined the influence of the difference in satellite sensor angles at 18:15 and 19:55 for NPP in Figure 6 to determine if sensor angle affected the uncertainly in these overlap sequences. Using the retrieved differences in radiance (Δ nLw) from the 18:15 and 19:55 orbits, we examined if product differences are correlated with the corresponding sensor zenith angle difference (Δ SZ). We tested the hypothesis that larger differences in retrieved products (Δ nLw) should be correlated with greater differences in sensor zenith angles (Δ SZ) if there is an angular impact. The results for the Δ 443nm , Δ 555nm channel and Δ chlorophyll (green) along the transect Line 2 are shown in Figures 6 a,b,*c* respectively. The differences in sensor angle ranged from -18 degrees to +8 degrees corresponding to 18:19 (west side of scan) from the 19:55 (east side). The difference shown in Δ nLw (a and b) (left vertical axis) show considerable scatter, especially for the Δ nLw 443nm channel. Whereas the Δ chlorophyll (right vertical scale) is more stable around about 0 mg^{m3}. Notice that there are differences in the Δ chlorophyll product in these sequential orbits, but these are not correlated with the changing sensor zenith. This lack of correlation with the sensor zenith suggests the products at these larger angles are being processed accurately and the observed differences can result from bio-optical changes and advective water mass movements that are occurring within the 101 minute sequence.

A possible explanation for the difference in the overlap products is found in the angular atmospheric removal process for ocean color processing. Besides the Rayleigh (Lr λ) correction, the atmospheric aerosol removal correction (Laλ) must be performed accurately or it will impact the differences in nLw. The aerosol radiance La 865nm is used as the reference radiance (NIR correction) for a down selection from the 80 aerosol models to identify the two specific aerosol models used to compute La(λ) for the ocean channels [2]. These aerosol models are used to determine the epsilon or the spectral Aerosol optical depth (La λ) that are removed from the total radiance at visible ocean channels (i.e. 443nm and 555nm) [6]. We evaluated the La 865nm across the transect to determine if there is an angular response and to examine which "pair" of aerosol models was selected for each orbit. Because these aerosol radiances should be similar within this 100 minute overlap period, the radiances and the aerosol model selected should be similar. Figure 7a, illustrates similar La 865nm radiance across the transect. The early orbit at 18:15 (blue) has a slightly elevated radiance at certain locations compared with 19:56 (black) and 18:45 (red - MODIS) radiance. There is not a standard bias or an angular bias

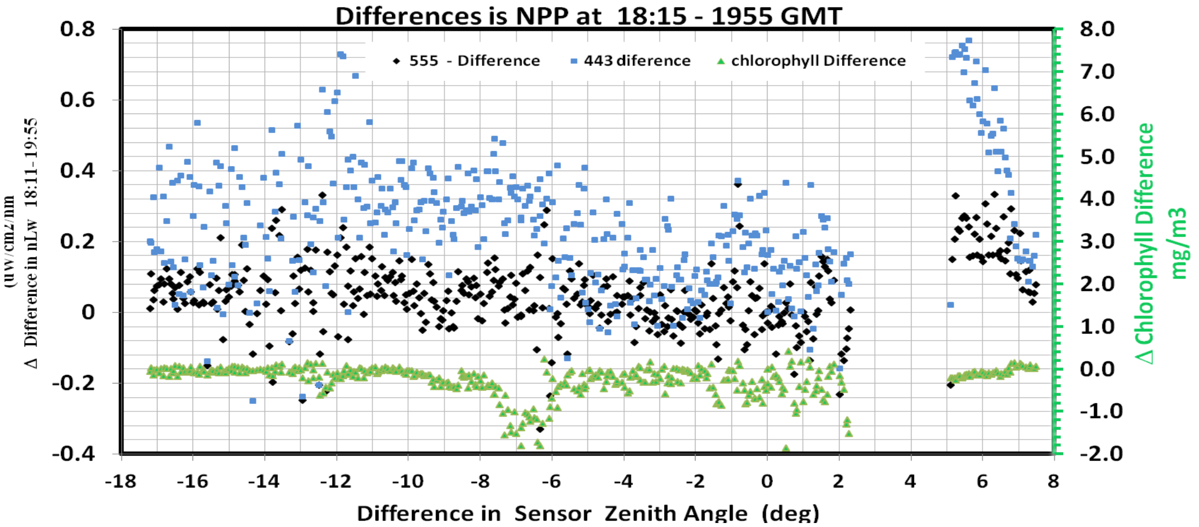

Figure 6. The difference in products from nLw and chlorophyll between the 101 minute orbit difference do not appear correlated with sensor zenith. Chlorophyll differences may be linked to bio-optical processes.

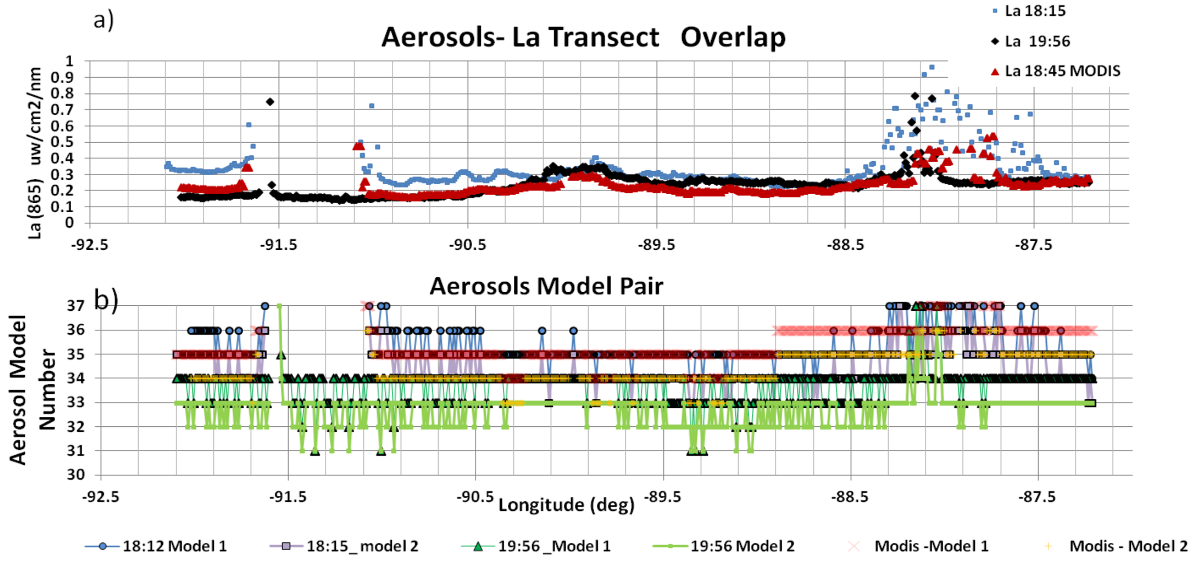

Figure 7. a) Aerosol radiance at 865 nm (La) across the transect is similar. Slight increase in the 18:15(blue) than for 19:55 or MODIS. b) Aerosol model pair used for epsilon selection of epsilon were similar: 18:15 used models 35-36, 34-35 , 19:55 used 32-33 and 33-34 and MODIS used 35-36.

associated with the differences in La865 for these different orbits. The two models selected for each of these orbits was similar *(*Figure 7b*)* and ranged from aerosol models 33 to 36. These models all have 75% humidity with differences in the % fine and coarse size fraction (Table 2).

Table 2 – Aerosol Models used along the transect

Model	% Humidity	% Fine size Fraction	% Coarse Size Fraction
32	75	50	50
33	75	30	70
34	75	20	80
35	75	10	90
36	75	5	95

The NPP 18:15 orbit used models 34, 35 and 36, which has a smaller % size fraction than the NPP 19:56 orbit which used models 32-34 and the MODIS orbit of 18:45 orbit which used the 35 and 36 aerosol models. There is increased scatter in the model selection at the east (about -87^o longitude) where there are larger differences in angles and more uncertainty in the La865nm especially at 18:15 orbit. However, note that the corresponding retrieved nLw at 443nm and 551nm (Figure 4 a,b) on the east part of the transect do not show this uncertainty between the different orbits. The nLw 551nm values are very similar across the transect. Also, the eastern part of the transect is east of the Mississippi River delta and can be influenced by the larger size land aerosols when compared to the western transect. This suggests that the aerosol model selection and the Laλ removal appears to be selected correctly and does not contain angular bias.

5. TEMPORAL CHANGES IN BIO-OPTICAL PRODUCTS

The temporal variability in satellite derived chlorophyll products between NPP-VIIRS orbital overlap and MODIS with approximately 100 minutes was investigated for several areas surrounding the US. Selected scenes include areas where rapid changes in bio-optical properties are expected. These occur in coastal areas where strong tidal movements affect frontal boundaries and where local winds affect mixing and biological responses in rapid growth and decay processes that affect ocean color.

The chlorophyll variability in the California Current (CC) system from Monterey Bay to southern California from June 25, 2012 is shown from 20:16 (NPP), 21:22(MODIS), and 22:27(NPP) GMT for S-NPP and MODIS (Figure 8a). The middle time MODIS product has slightly lower values than the bracketing NPP products, however the features are similar (note the log chlorophyll scale.) Changes in the chlorophyll are observed along coastal regions which are prone to the hourly changes in bio-optical responses that are a possible result of growth, decay and advection of water masses. Subtle changes in coastal chlorophyll features are observed as we zoom into the Monterey Bay (Figure 8b) especially along the chlorophyll fronts (A, B) and upwelling regions in the northern bay. There are small feature movements along these features that indicate a subtle biological change. This is best observed using the NPP-VIIRS sensor, as the products are similar as described before, but with the added advantage of using the same satellite sensor. Observed within Monterey Bay, the 20:16 orbit shows a patch of dark red (10mg^{m3}) in the center of the Bay (location C). This elevated chlorophyll is observed on the coast approximately 100 minutes later in the 22:27 orbit.

Temporal changes in the chlorophyll concentration along the Gulf Stream front off of Florida within the 100-minute sequence for NPP-VIIRS are shown in Figure 9 a,b. The Gulf Stream frontal boundary represents high velocities with high current shear which influence cross frontal mixing processes and localized vertical water mass movement. The enlargement of the boundary in the lower panels (Figure 9b) shows northerly movement of chlorophyll features that have also undergone change in the surface chlorophyll signature. The “shingle” structures along the Gulf Stream front at A and B have moved northward and the structure has diffused to increased higher chlorophyll features. The change at location at Figure 9C appears to show a low chlorophyll region filled by an eastward moving chlorophyll patch with the 100-minute period.

These examples clearly show that biological changes are occurring within a 100-minute period. Determining if these changes are a result from water mass advection and/or biological processes is unclear. However, these examples provide evidence that satellite product validation and uncertainty must consider rapidly changing bio-optical properties in when determining satellite product uncertainty.

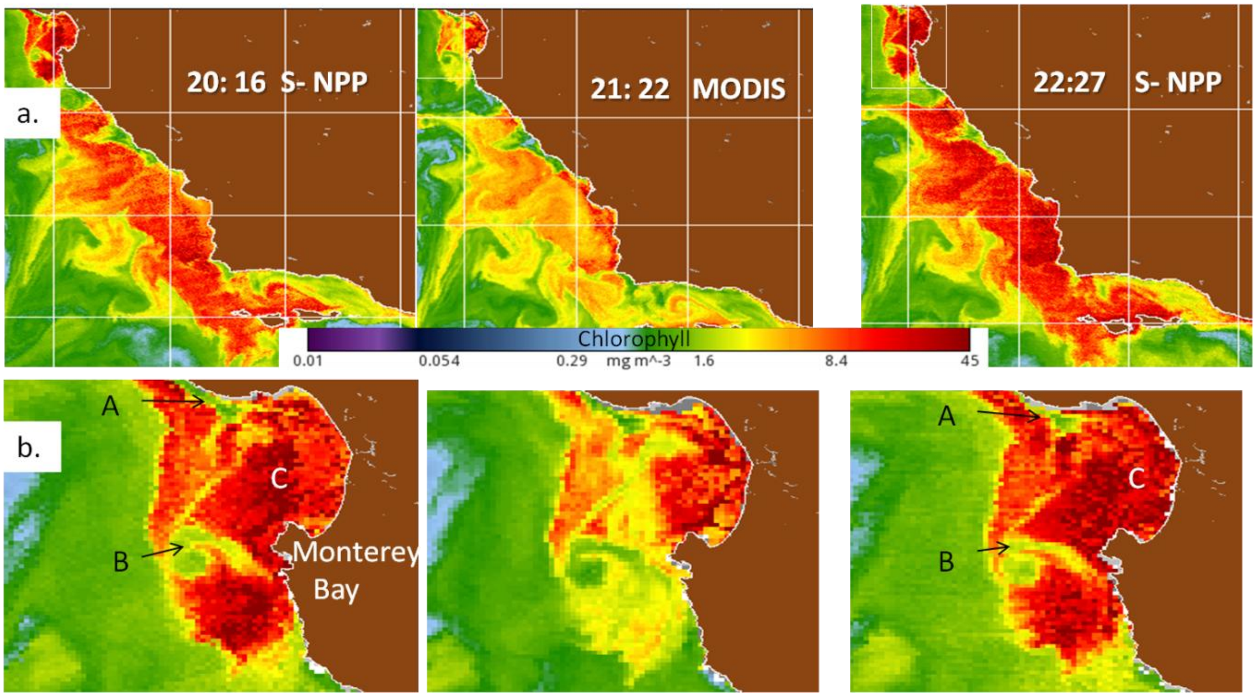

Figure 8. a) Southern California chlorophyll sequence within 121 minutes derived from S-NPP and MODIS for June 25, 2012 from 20:16 - 22:27 GMT. b) Monterey Bay panels show possible bio-optical changes from upwelling and advective changes along the coasts.

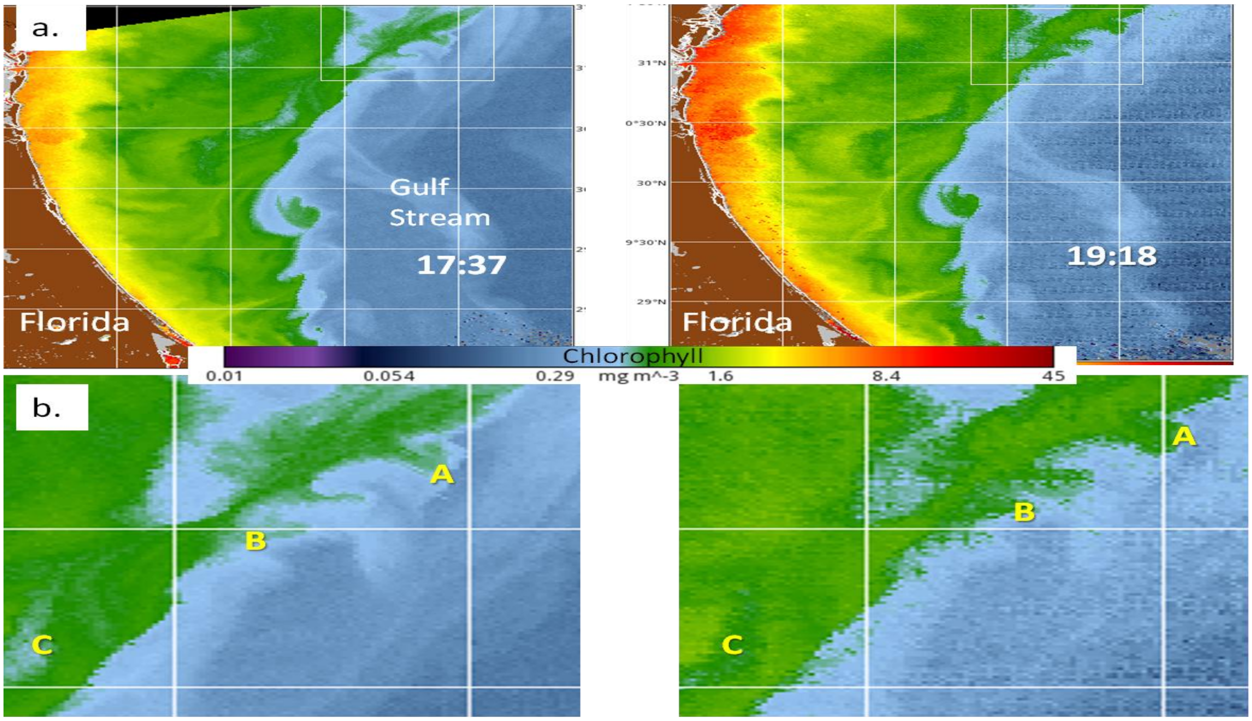

Figure 9. a) November 3, 2012, S-NPP Chorophyll along the north wall of the Gulf Stream off of Florida from 17:37 and 19:18 GMT b) enlarged area along the front shows advective displacement of the chlorophyll feature-es.

6. CONCLUSIONS

The changes in the bio-optical products derived from ocean color were evaluated using the image overlaps from successive orbits of S-NPP in addition to the MODIS-Aqua satellite. These three sequential ocean color products were collected within about 100 minutes to determine the temporal changes in chlorophyll, and normalized water leaving radiance at 555nm and 443 nm. Temporal changes can occur as a result from water mass movement, bio-optical changes, and inaccuracy in sensor characterization and processing. The differences between MODIS and S-NPP are most likely associated with sensor specifics; however, using the overlap of the S-NPP sequence removes some of this uncertainty. S-NPP overlap occurs at the left and right side of the swath at sensor zenith angle 50-70 degrees and strong evidence was not found indicating the influence of angular dependence on the orbital product difference did not show strong evidence. The sequential changes in nLw at 555nm was small in comparison to nLw at 443nm, which shows higher scatter. The retrieved chlorophyll orbits did not appear to be influenced by angular affects although differences in higher (coastal) concentrations was more evident. The removal of the aerosols (La) and aerosol models appears to be similar in the sequential orbits and therefore appears to be handling the angular effects correctly.

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The resulting sequential chlorophyll products within the 100 minute period appears to be related to the changes in the bio-optical properties, especially in the rapidly changing environments of tidal and coastal areas, as well as in rapidly moving currents, notably the Gulf Stream. Although the errors introduced with the sensor characterization and processing are not completely accounted for, the initial examination shows a unique utility of using three sequential products within a 100 minute period for monitoring rapidly changing ocean processes.

The study concludes that the variability in ocean color products with 100 minute periods establishes an uncertainty of the products when used for validation and calibration with *in situ* observations. This uncertainty of the chlorophyll product from these sequential orbits identifies a temporal coherence scale for different water types and processes which must be addressed in validating satellite products. For example, the validation of chlorophyll products along the Gulf Stream front has a short temporal coherence (about 15 minute constraint for matchup) and the bio-optical uncertainty is about 70 % within 100 minutes.

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