Diurnal changes in ocean color in coastal waters

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ABSTRACT

Coastal processes can change on hourly time scales in response to tides, winds and biological activity, which can influence the color of surface waters. These temporal and spatial ocean color changes require satellite validation for applications using bio-optical products to delineate diurnal processes. The diurnal color change and capability for satellite ocean color response were determined with in situ and satellite observations. Hourly variations in satellite ocean color are dependent on several properties which include: a) sensor characterization b) advection of water masses and c) diurnal response of biological and optical water properties. The in situ diurnal changes in ocean color in a dynamic turbid coastal region in the northern Gulf of Mexico were characterized using above water spectral radiometry from an AErosol RObotic NETwork (AERONET -WavCIS CSI-06) site that provides up to 8-10 observations per day (in 15-30 minute increments). These in situ diurnal changes were used to validate and quantify natural bio-optical fluctuations in satellite ocean color measurements. Satellite capability to detect changes in ocean color was characterized by using overlapping afternoon orbits of the VIIRS–NPP ocean color sensor within 100 minutes. Results show the capability of multiple satellite observations to monitor hourly color changes in dynamic coastal regions that are impacted by tides, re-suspension, and river plume dispersion. Hourly changes in satellite ocean color were validated with in situ observation on multiple occurrences during different times of the afternoon. Also, the spatial variability of VIIRS diurnal changes shows the occurrence and displacement of phytoplankton blooms and decay during the afternoon period. Results suggest that determining the temporal and spatial changes in a color / phytoplankton bloom from the morning to afternoon time period will require additional satellite coverage periods in the coastal zone.

Keywords: Ocean Color, Diurnal, Uncertainty, SNPP VIIRS, AERONET, Validation, Orbit Overlap, GEOCAPE,

1. INTRODUCTION

The changes in ocean color that occur throughout the day are important for defining ocean processes with satellite radiometry. Water color can change rapidly throughout the day especially in coastal areas where dynamic ocean processes occur (Wang et al. 2013). Ocean color is defined as the spectral water leaving radiance (nLw_λ) or remote sensing reflectance (RRS_λ), and are used to define water properties including chlorophyll and inherent optical properties (absorption/scattering) (Lee et al., 2005 , Arnone et al 2006). Ocean processes that can influence rapidly changing ocean color on the order of hours can include: 1) advection of water masses such as fronts and river plumes that respond to wind events, tidal forcing and dynamic circulation events and 2) water mass bio-geo-optical changes that include: a) the growth and decay of phytoplankton blooms, b) upwelling and downwelling of vertical optical layers and c) particle settling and resuspension events (Curran et al., 2007). These diurnal changes in ocean color provide a unique capability to help characterize these processes, provided the temporal element of ocean color response is recognized.

Satellite ocean color products from polar orbiting satellites collect imagery on daily time scales and typically are not used to identify these diurnal processes. The calibration and validation of products from ocean color sensors, especially in dynamic coastal areas does not usually account for the diurnal changes in ocean color and assumes a relatively temporally stable daily product. For example the daily chlorophyll products from Suomi NPP VIIRS or MODIS-Aqua in coastal areas are assumed representative of the daily product and relatively stable throughout the day. The uncertainty for daily temporal variability of the chlorophyll product and how it changes across the coastal region is not well defined. In offshore waters where temporal dynamic processes are reduced, the color signatures are more homogeneous and can be more diurnally stable. Methods for calibration and validation of satellite products are easier and better defined for more spatially and temporally homogenous offshore waters than in waters with strong diurnal changes.

Our objective is to examine the diurnal changes in ocean color that can occur in coastal regions and determine the capability of the present polar orbiting satellites to identify and validate these changes. We will examine present AErosol RObotic NETwork (AERONET) SeaPRISM data at WavCIS in the northern Gulf of Mexico, which is used for satellite ocean color calibration and validation in coastal areas, to determine the diurnal changes in ocean color. Our objective will also use the VIIRS orbital overlap imagery to determine the capability to examine diurnal changes in ocean color imagery at the same location. We will determine the uncertainty of the VIIRS diurnal overlap products by comparing with in situ data from ship measurements and AERONET SeaPRISM. Our efforts will validate the ocean color diurnal products in coastal regions to demonstrate the changes in ocean color that can occur in dynamic coastal regions such as the northern Gulf of Mexico. Our objective will examine possible products from diurnal changes in ocean color that include phytoplankton bloom and decay and surface currents.

2. METHODS

Orbital overlap / coincident repetition of satellite ocean color can be obtained using the sensor viewing overlap between sequential orbits. Evaluating 2 satellites such as MODIS and VIIRS for diurnal ocean color changes can be challenging since these are two different unique sensors with different spectral channels and calibration, thereby introducing some comparative uncertainty between the two sensors. However, the VIIRS polar orbiter has orbital overlap where coincident ocean color data is collected at the same location from Orbit 1 and Orbit 2 within ~100 minutes of each other. In the Gulf of Mexico (at 30^{o} latitude over the AERONET site and several data matchups from ship measurements) the VIIRS sensor has overlapping orbits on the right and left side of the swath from repetitive orbits with a coverage area of approximately 500 nautical miles. The dual VIIRS orbits cover an area of approximately 55 – 70 degrees sensor zenith angle on the left and right side of swath as shown in Figure 1. This VIIRS overlap has a revisit time of approximately every 4-5 days at this latitude in the Gulf of Mexico. The MODIS-Aqua orbit is near the same time period in the afternoon. The VIIRS ocean color data were processed using NASA L2gen (Wardell et al., 2013) to derive the bio-optical properties for each orbit so that the changes in the satellite water leaving radiance (nLw) and changes in the bio-optical properties could be evaluated (Ladner et al 2013, Arnone et al., 2013.2014).

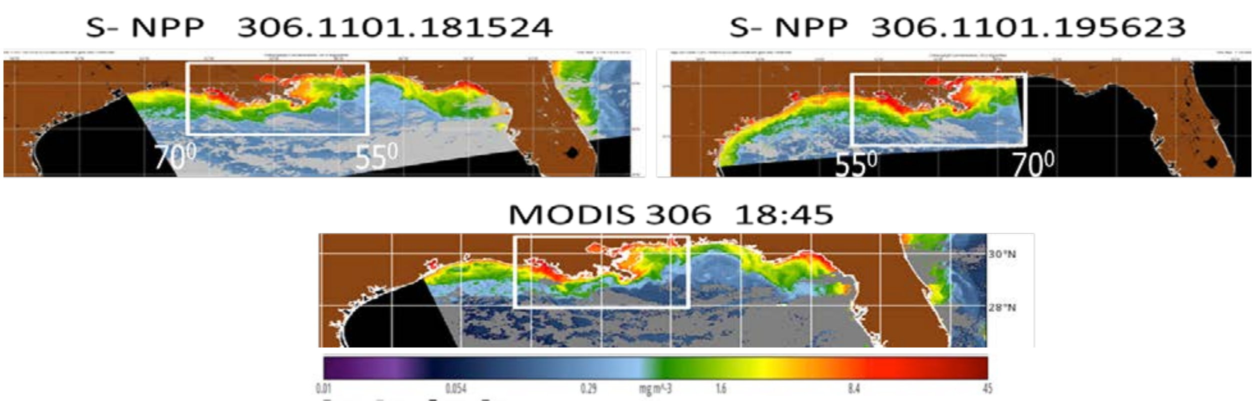


Figure 1: Diurnal chlorophyll products in Gulf of Mexico orbital overlap of S-NPP VIIRS and MODIS Aqua for November 01, 2014 with GMT overpass Times (NPP #1: 1815GMT, NPP#2: 1956GMT, MODIS: 1845GMT).

The AERONET SeaPRISM at WavCIS in the Northern Gulf of Mexico collects data daily at 15-30 minute increments on a continual basis from 2014 to present. These data are sent to NASA-AERONET where the data are processed and screened from level 1 to 1.5 to remove corrupt data such as surface glint (Holben et al., 1998, Zibordi et al., 2009). Daily AERONET nLw's (multispectral) are available (level 1.5) to reveal the diurnal changes in ocean color that can occur throughout the seasonal cycle. Additional International AERONET sites at other locations are available to confirm the results that are observed at the WavCIS site. Examples of the changes in ocean color (nLw @ 551nm and 443nm) at the AERONET site are shown in Figure 2. Using these data sets we are able to compare and quantify the changes in satellite-derived ocean color with the AERONET changes.

3. AERONET – VIIRS OVERLAP COMPARISONS

VIIRS overlapping ocean color nLw's for February 11 and December 25, 2014 were matched up with the diurnal measurements at the WavCIS site (Fig. 2), showing the uncertainty of the satellite and the changes in ocean color. The insitu nLw at 443 (purple) and 551nm (blue line) at the WavCIS site is shown to change rapidly during the day. A rapid decrease in nLw 551 of approximately 40% (1.25 to .8 μw/cm^2/sr) within 1 hour was observed on February 11 at 18:30 GMT. Similarly on December 25 a steady decrease of ~ 40% in nLw from morning (14:38 GMT) to afternoon (19:00 GMT) was observed at 443 and 551 nm. Additional examples of daily changes in nLw were also observed for other yearly time periods.

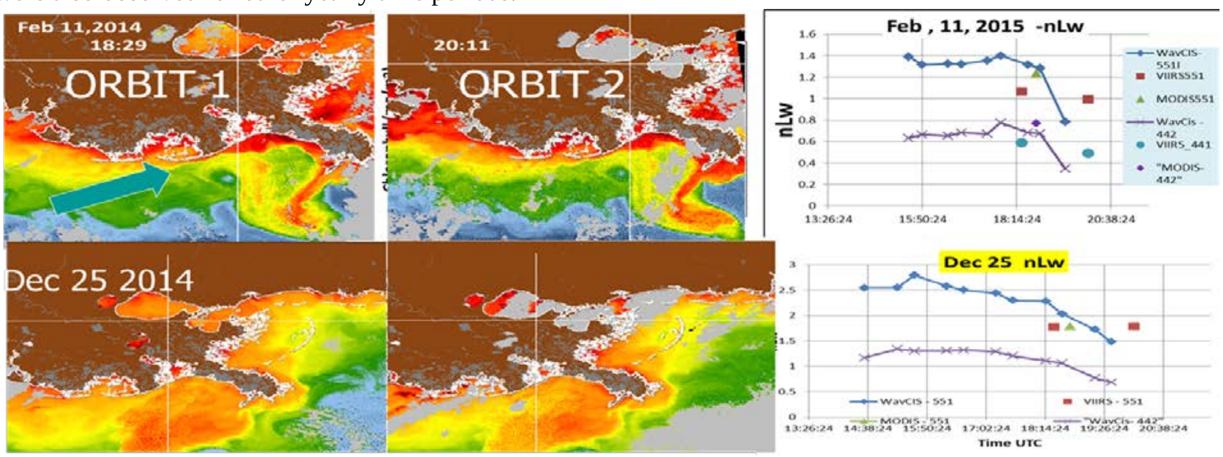


Figure 2: WavCIS AERONET site located at arrow. The overlap of VIIRS Orbit 1 and 2 for February 11 and December 25 for each day shows the ocean color chlorophyll products within 100 minutes. Plots show WavCIS (blue and purple lines) ocean color changes in the nLw throughout the day and the VIIRS (red) and MODIS (purple) matchup.

The matchup of nLw for VIIRS and MODIS with AERONET (Fig. 2) for the corresponding time periods shows a decreasing trend seen at the WavCIS site, with a higher level of uncertainty later in the day. The satellite matchup uncertainties are possibly related to: 1) the spatial variability of the satellite coverage of ~1500 m (high zenith angles) ground resolution (pixel size) compared to the WavCIS site and 2) corrections for sensor and solar angles including the water Bidirectional reflectance distribution function (BRDF) (Bailey et al., 2006)for the high angles in orbital overlap.

Another example for December 9, 2014 (Fig. 3D) shows the diurnal color change in the nLw and chlorophyll in the Northern Gulf of Mexico. Note the changes in the VIIRS ~100 minute overlap matchup with the daily changes observed at WavCis. Again, the hourly changes in the ocean color at the WavCIS site are shown to be highly variable for the nLw 551nm and the 443nm channels with a decrease from 1.6 to .4 μw/cm^2/sr in a period of 45 minutes. The corresponding chlorophyll values from these nLw values show the expected diurnal change from 2 to 4 mg/m3 within the 45 minute period. The matchup of the ocean color products (nLw and derived chlorophyll) from 2 VIIRS overlaps and MODIS clearly shows a close relationship and the trend of the diurnal cycle at WavCIS. This indicates the satellite ocean color products have the capability to identify hourly changes that can occur in surface waters. For the Dec 9 example, the processing for sensor, solar angles, BRDF, and atmospheric correction for satellite ocean color appear to be better, since the matchups are much closer with AERNET.

The chlorophyll difference (Fig. 3C) between orbit 1 (Fig. 3A) and orbit 2 (Fig. 3B) of the VIIRS overlap shows areas of phytoplankton blooms and decay. The negative (red) differences in Fig. 3C represent an increase in chlorophyll that reached concentrations of +3 mg/m^3 during the 100 minute period. Elevated chlorophyll is observed in the 20:31 GMT image (Fig 3B). Similarly, positive values (blue areas; Fig 3C) representing chlorophyll decay were observed, especially along coastal regions and at the WavCIS site where there is a small area with reduced chlorophyll.

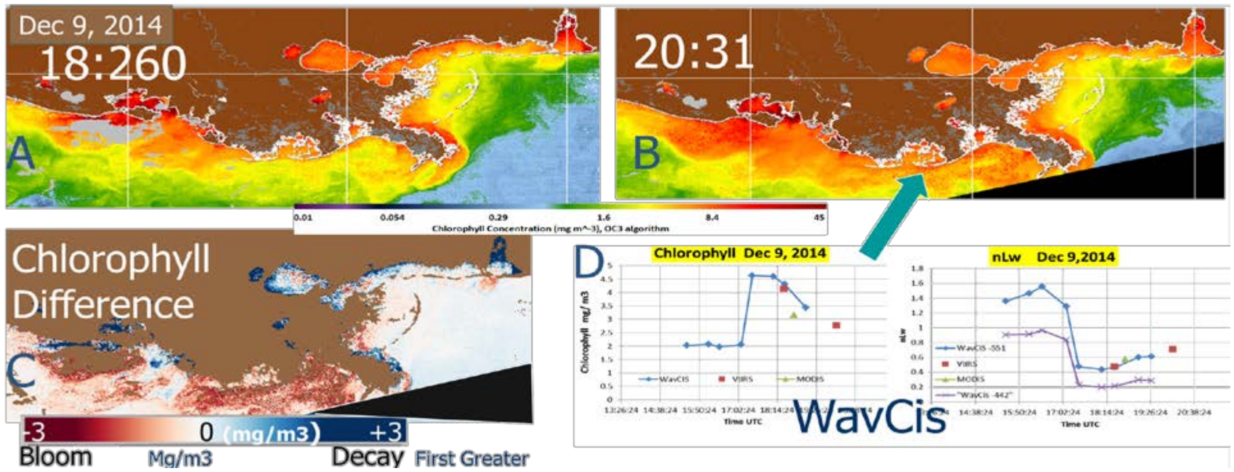
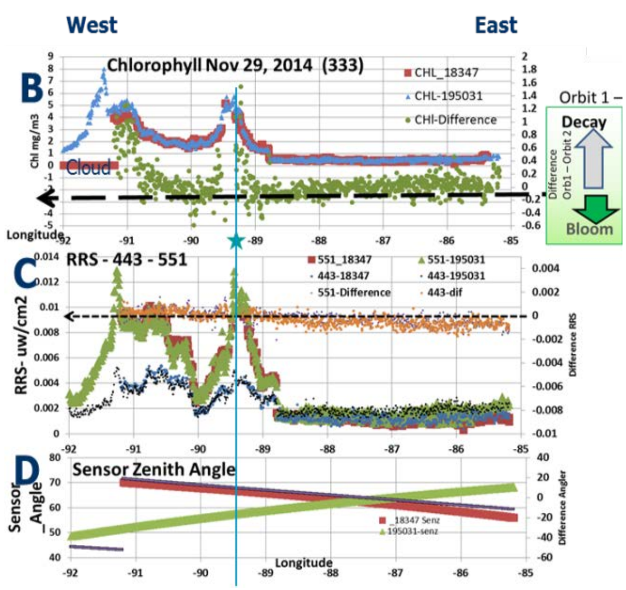


Figure 3- A) B) VIIRS Overlap Chlorophyll for December 9 C) Chlorophyll difference image represents Orbit 1 minus Orbit 2. D) Plots of diurnal ocean color at the AERONET WavCIS site for nLw (551, 443nm) and chlorophyll with corresponding VIIRS (red) and MODIS (green) matchup.

4. VIIRS PRODUCT OVERLAPS

To evaluate the capability for the VIIRS ocean color satellite to retrieve accurate ocean color products for the orbital overlap imagery (Fig. 4), we evaluated the influence of the changes which occur between orbits along a transect line across angular swaths from approximately 55 to 70 degrees for each orbit. The location of the east-west transect crosses several coastal fronts with a large range in chlorophyll values. The chlorophyll transect lines (Fig. 4B) shows similar patterns in orbit 1 (1834GMT - red) and orbit 2 (1959GMT - blue). The chlorophyll concentration difference (orbit1 - orbit2) is small, and negative values represent a bloom as described previously. Negative differences in chlorophyll occur at fronts such as the Mississippi Plume front (blue Star). The changes and differences in the Rrs for 443 and 551nm (Fig. 4C) are similar. The sensor zenith angle for orbits 1 and 2 (Fig. 4D) along the transect shows the changes in the overlap ranging from 50 – 70 degrees with both orbits having some strong differences. For example at -91^{oW} longitude, Orbit 1 has a sensor zenith angle of 70 degrees and Orbit 2 has an angle of 55 degrees. At this longitude, the difference in Rrs and chlorophyll was slightly higher suggesting the difference may be associated with larger sensor angles. At locations where there is less of a difference between orbital zenith angles, there are smaller differences in the ocean color.



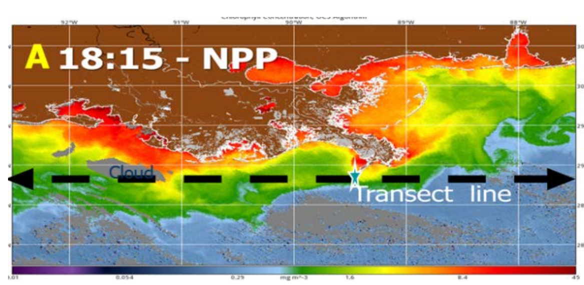


Figure 4: VIIRS overlap color changes across the transect line for November 29, 2014.

A) Location of east-west transect line (black dash)

B) Chl from Orbit 1- (1834GMT - red) and 2 (1550 GMT - blue) and Chl difference (green) shows bloom (-) and decay (+) regions

C) Spectral changes in Rrs 551 and 443 and difference

D) Sensor zenith angle orbit 1 and 2 and angle difference.

5. UNCERTAINTY IN DIURNAL OCEAN COLOR

During the NASA GEOstationary Coastal and Air Pollution Events (GEO-CAPE) September 2013 cruise in the northern Gulf of Mexico (add Ref X), stations were collected in coastal waters during VIIRS orbital overlaps. The diurnal changes between these orbital overlaps in the coastal region can be used to estimate the uncertainty in ocean color products. Figs. 5A and 5B show the locations where several stations were collected at locations A and B, both during VIIRS overlaps. The spectral Rrs matchup of the 5 VIIRS channels at these locations with both the in situ and VIIRS orbit 1 and 2 shows the differences in Rrs. The percent spectral uncertainty (Fig. 5C) at a station between the VIIRS ~100 minute orbits range from 4% at 410 nm to 31% at 671 nm. The in situ observations are closer to the second orbit time.

A comparison of the in situ backscattering at 440 nm and absorption at 486 nm with each of the VIIRS overlaps orbits for six observations is shown in Fig. 5D. These differences between the three in situ stations at locations A and B and the VIIRS overlap could be associated with diurnal changes in the diurnal bio-optical processes which can occur within 100 minutes. The percent changes, in the backscattering and absorption products from VIIRS overlap at these 3 stations showed a similar range to the Rrs and nLw changes, with values ranging from 17% to 35%. This percentage was similar to the change observed in the AERONET ocean color diurnal changes at WavCIS. When validating and calibrating ocean color products in the coastal region, measurements are required to be near coincident with the time of overpass to account for diurnal processes which can change the ocean color significantly within these short time periods.

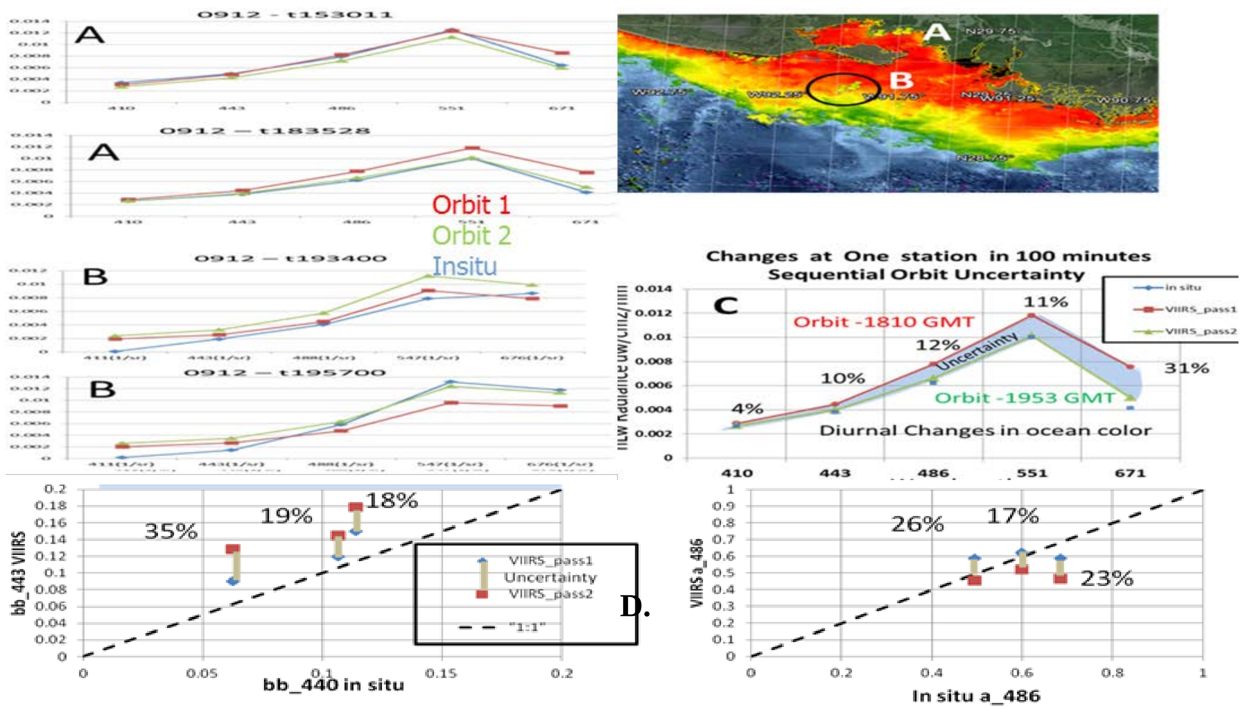


Figure 5: Plots show the spectral Rrs uncertainty on September 12, 2013 at Stations (A,B) between in situ RRS and VIIRS overlap, C) Percent spectral uncertainty ata station of the VIIRS overlap D) uncertainty of in situ,backscattering at 440 nm and absorption at 486 nm with percent diurnal changes in VIIRS overlaps of bb and absorption.

6. DIURNAL OCEAN COLOR PRODUCTS

Another example (Fig. 6) illustrating the ocean color changes that can occur on a daily basis is shown for November 29, 2014 with the VIIRS orbital overlaps. The chlorophyll imagery from orbit 1 and 2 look very similar, however the difference (orbit 1 from orbit 2) between the chlorophyll shows the location of increased chlorophyll with time representing a diurnal bloom on the Mississippi shelf, which occurred within the 100 minute period (Fig. 6C,D). The chlorophyll changes of +/- 1 mg/m^3 range was not as great as previous examples (Fig. 3), which suggest that the processes which influence diurnal changes in ocean color change both spatially and temporally. These temporal diurnal changes were also observed in different months of AERONET diurnal changes (Fig. 7). Figure 7 shows days in 2014 in which the WavCIS AERONET returned > 8 radiance matchups for one day, and that have concurrent data from VIIRS overlap (two images) and MODIS-Aqua. The red and blue bars represent the average of all three satellite measurements, and daily AERONET average, respectively, with the standard deviation showing the extent of variation among satellites, and diurnal changes.

The location of ocean color frontal movement or water mass advection is also observed in the chlorophyll difference image (Fig. 6D). A Mississippi river plume front is shown as an elongated feature of decreased chlorophyll (blue). Rapid temporal color change at ocean fronts confirms the importance of short time constraints for satellite matchup validation due to water mass movements.

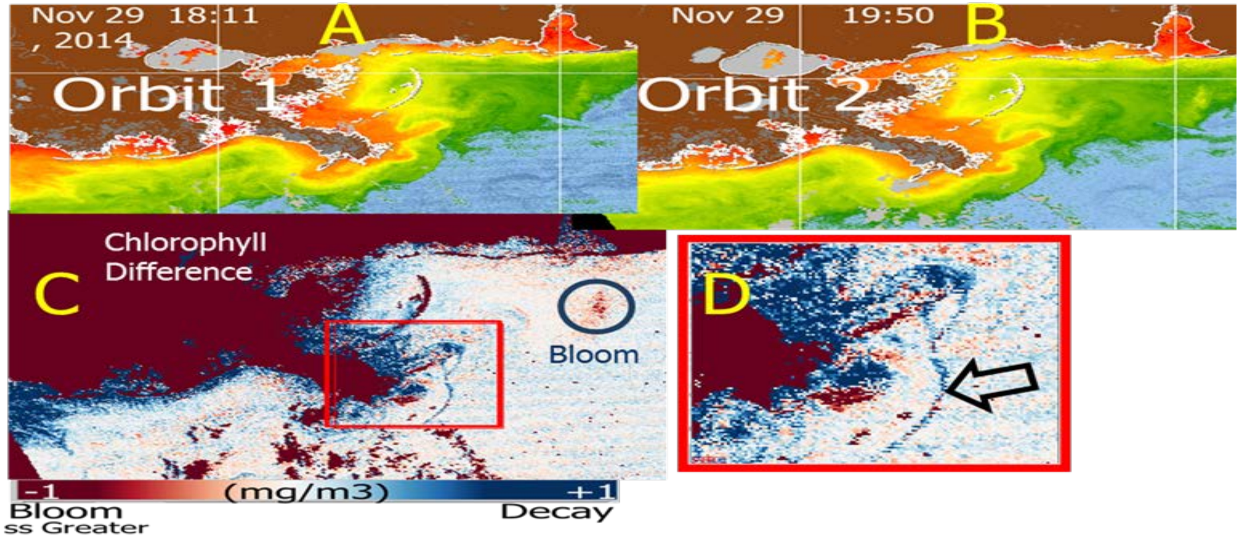


Figure 6: VIIRS Diurnal changes in chlorophyll November 29, 2014 between orbit 1(A) and 2 (B). The difference in chlorophyll between the orbits shows the location on bloom (C). Chlorophyll difference showing Mississippi Plume advection (D) - Zoom.

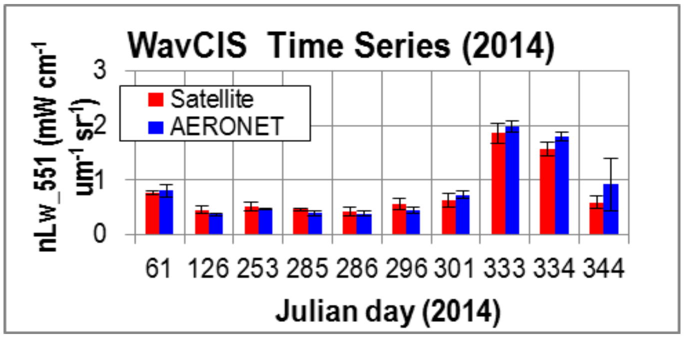


Figure 7: Time series from WavCIS AERONET site in 2014, showing days with 8 – 11 WavCIS measurements, matched up with the average of three satellite measurements (VIIRS x 2 + MODIS-Aqua), from the same day. The error bars represent the standard deviation, which may be interpreted as the satellite/in situ uncertainty in conjunction with diurnal changes.

These types of diurnal color changes occurring in surface waters associated with water mass advection can be used to estimate surface currents (Yang et al., 2015) provided advection can be separated from bio-optical changes. There are certain ocean color properties that can be associated with water mass advection processes rather than bio-optical processes. Figure 8 illustrates how the use of changing ocean color products from the diurnal VIIRS orbital overlaps can be used to estimate surface currents. The Maximum Cross Correlation method (MCC) that is based on spatial gradients between each ocean color products for each orbit was used to estimate surface currents. Four different ocean color products: backscattering 551nm, chlorophyll, beam attenuation 551nm and Rrs 551nm from the VIIRS diurnal overlap color imagery within 100 minutes of each other, were used to generate the surface currents. Certain ocean products such as bb551 and RRS551 were capable of retrieving more surface currents than other products which indicate they may more closely related to advection of water masses from diurnal changes than diurnal bio-optics changes such as the Chlorophyll product.

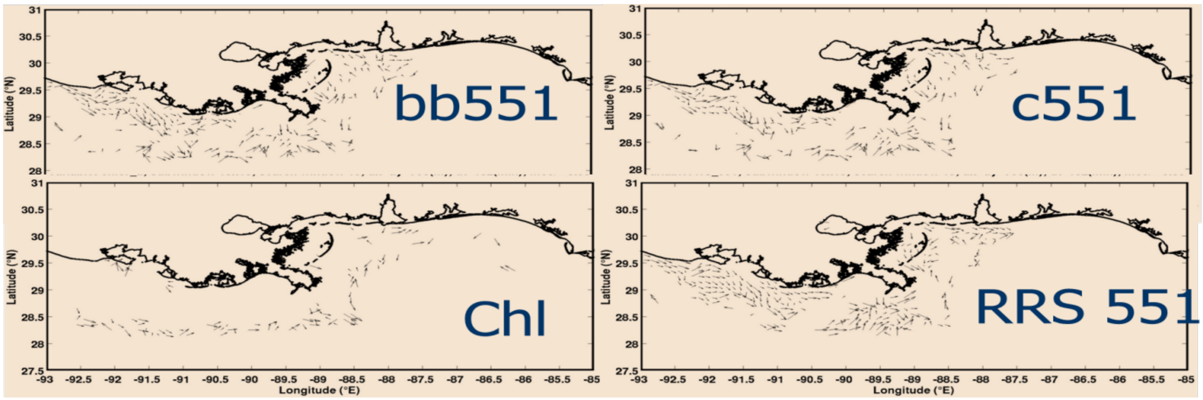


Figure 8: Diurnal changes from VIIRS overlaps in ocean color can be used to estimate surface currents from these 4 different color products. Each product shows different number of retrieved surface current vectors (Yang et al., 2015).

7. CONCLUSIONS AND DISCUSSION

Changes in ocean color occurring during hourly diurnal cycles throughout the day have been shown by the AERONET – WavCIS SeaPRISM site in the northern Gulf of Mexico. The color changes were not consistence throughout all days but were highly variable in response to dynamic coastal processes. Rapid color changes were shown to occur at WavCis as high as 40% within a 60 minute period. The polar orbiting ocean color satellites show changes in ocean color within 100 minutes in the coastal zone of the northern Gulf of Mexico using the same sensor VIIRS and consecutive orbital overlaps. Using the same VIIRS sensor for overlap supports inter-satellite consistency. The changes in ocean color within 100 minutes between the VIIRS overlaps were confirmed and verified by the WavCIS AERONET to follow the diurnal trends of both the water leaving radiance (nLw) and derived bio-optical products.

The uncertainty of the spectral changes which occur in ocean color orbital overlaps was shown to range from 4 to 31% changing with time and space. These changes in ocean color can occur in dynamic coastal areas and in response to water mass advective processes and bio-optical changes in water properties.

The impact of different satellite sensor and solar angles and the impact on the retrieved ocean color were examined to confirm the VIIRS overlaps are capable of retrieving the hourly changes in ocean color. Different levels of uncertainty between ocean color satellite and in situ matchups were shown indicating that diurnal variability in ocean color can change in time and space.

Matchups of in situ and orbital overlaps of VIIRS overlaps show the uncertainty that can occur with the 100 minute periods in coastal areas. These changes must be considered when validating and calibrating ocean color sensors in coastal areas because of the dynamic nature of the color signatures.

New ocean products can be developed based on diurnal changes in ocean color properties to characterize processes. Hourly changes in ocean color can be used for defining both the physical processes such as water mass advection or surface currents and biological -optical processes. Chlorophyll difference between the 100- minute VIIRS overlaps show areas of potential blooms (growth) and decay. These changes can be confirmed using the AERONET WavCIS site. Surface currents were computed using diurnal VIIRS overlap color products. Certain color products are better at producing surface currents (bb550) between multiple hourly/overlap images than others (chl).

Diurnal processes that can cause a chlorophyll bloom include upwelling of optical layers into the first optical depth and enhanced surface pigments. These diurnal changes in ocean color should occur in both in situ and ocean color data. The processes that are causing these changes need to be further examined in coastal regions.

Results confirm satellite ocean color can provide a unique capability to capture diurnal changes in ocean color especially in coastal areas. The rapidly changing ocean color signatures can provide tools for monitoring diurnal processes in the coastal zone and support the requirements for a geostationary ocean color satellite.

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