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Estimating sea surface salinity in coastal waters of the Gulf of Mexico using visible channels on SNPP-VIIRS

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ABSTRACT

Sea surface salinity is determined using the visible channels from the Visual Infrared Imaging Radiometer Suite (VIIRS) to derive regional algorithms for the Gulf of Mexico by normalizing to seasonal river discharge. The dilution of river discharge with open ocean waters and the surface salinity is estimated by tracking the surface spectral signature. The water leaving radiances derived from atmospherically-corrected and calibrated 750-m resolution visible M-bands (410, 443, 486, 551, 671 nm) are applied to bio-optical algorithms and subsequent multivariate statistical methods to derive regional empirical relationships between satellite radiances and surface salinity measurements. Although radiance to salinity is linked to CDOM dilution, we explored alternative statistical relationships to account for starting conditions. *In situ* measurements are obtained from several moorings spread across the Mississippi Sound and Mobile Bay, with a salinity range of 0.1 - 33. Data were collected over all seasons in the year 2013 in order to assess inter-annual variability. The seasonal spectral signatures at the river mouth were used to track the fresh water end members and used to develop a seasonal slope and bias between salinity and radiance. Results show an increased spatial resolution for remote detection of coastal sea surface salinity from space, compared to the Aquarius Microwave salinity. Characterizing the coastal surface salinity has a significant impact on the physical circulation which affects the coastal ecosystems. Results identify locations and dissipation of the river plumes and can provide direct data for assimilation into physical circulation models.

Keywords: Sea surface salinity, Suomi-NPP, VIIRS, ocean color, coastal remote sensing

1. INTRODUCTION

The spatial distribution of sea surface salinity in coastal and shelf waters is important for the parameterization of the dynamic physical exchange processes that deliver terrestrial carbon into the world ocean. The introduction of freshwater into the ocean system serves as an important pathway for many biogeochemical processes, in addition to creating a high variation in density that can drive coastal circulation. Several experimental and operational models exist that attempt to characterize, monitor, and predict these exchange processes, but are often limited by a lack of high spatial and/or temporal resolution data in coastal regions that can be used for assimilation. While existing technology based on microwave sensing from the Aquarius/SAC-D and Soil Moisture and Ocean Salinity (SMOS) missions enables the retrieval of accurate (± 0.2 psu) ocean salinity measurements at larger spatial scales (30 - 100 km), near-coastal retrievals are limited by signal contamination from land. In addition, these microwave sensors cannot spatially resolve the rapidly changing dynamics of coastal waters and river plumes.

Higher resolution salinity products may be available by using the visible channels of existing ocean color sensors and exploiting the “quasi-conservative” nature of various bio-optical properties, which can be detected remotely. The Suomi National Polar-orbiting Partnership (SNPP) satellite with the Visual Infrared Imaging Radiometer Suite (VIIRS), has five available ocean color bands at a spatial resolution of 750-m, offering increased spatial and temporal coverage of coastal regions compared to current L-band radiometry. The objective of this study is to develop a regional sea surface salinity algorithm for the Northern Gulf of Mexico, based on comparisons of seasonal *in situ* data with remotely sensed spectral radiance and bio-optical properties. The increased temporal and spatial scale of a validated salinity product will enable the enhanced detection of complex hydrodynamic features, thus potentially providing an improved data assimilation parameter.

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2. DATA DESCRIPTION

2.1 Study area

The Mississippi coastal estuarine system encompasses several salt-influenced bays, the Mississippi Sound, and the Mississippi Bight. Primary seawater input to the estuarine system occurs through passages located between these six offshore barrier islands. The freshwater introduced to the Mississippi Sound arrives through numerous rivers which cover the entire geographic range of the MS Coast and extend eastward into Mobile Bay. Additionally, episodic freshwater “pulses” from the Mississippi River can also influence this region. Given the shallow (average depth of MS Sound = 3 m) and well-mixed nature of this region, variations in salinity generally extend horizontally from the mouth of the rivers and bays, with minimal vertical stratification north of the barrier island passes[1,2].

2.2 *In situ* data collection

To develop the VIIRS salinity algorithm, *in situ* conductivity and temperature data were obtained from five USGS platforms (Site no: 301104089253400, 301429089145600, 301912088583300, 301527088521500, 301849088350000; see Figure 1 for locations) and one NOAA/NDBC platform (Station MBLA1) for January – October, 2013. Salinity was calculated from conductivity and temperature and the data were averaged between 1800 – 2000 GMT, corresponding to the approximate VIIRS overpass time. Salinity values ranged from 0 – 33 psu for this study.

2.3 Satellite remote sensing data processing

Level 1 VIIRS sensor data records (SDRs) from January to October, 2013 were downloaded from NOAA’s Comprehensive Large Array-data Stewardship System (CLASS, www.class.noaa.gov). All files were processed from SDRs (raw radiance + calibration) to Level-3 (fully calibrated, atmospherically corrected and mapped) using the Naval Research Laboratory’s Automated Processing System (APS). All data were processed were processed using the standard Gordon/Wang[3] atmospheric correction at a resolution of 750-m, utilizing multi-scattering and iterative NIR correction[4]. Standard flags were used to mask interference from land, clouds, sun glint, and other potential disturbances to the radiance signal. Spectral (410, 443, 486, 551, 671) remote sensing reflectance (rrs) and total spectral absorption (a_QAA[5]) satellite products were produced for this time series. The closest single satellite pixel was extracted corresponding to the *in situ* location for the year 2013, yielding 327 total matchup points that were used for the VIIRS salinity algorithm. In addition, a time series of satellite data was extracted from the mouth of the Mobile River, AL for 2013 (Dashed circle, Figure 1).

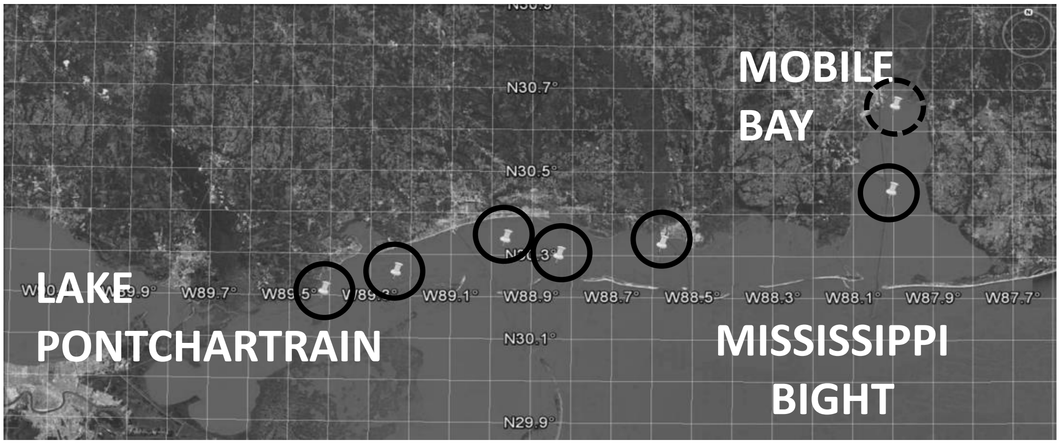
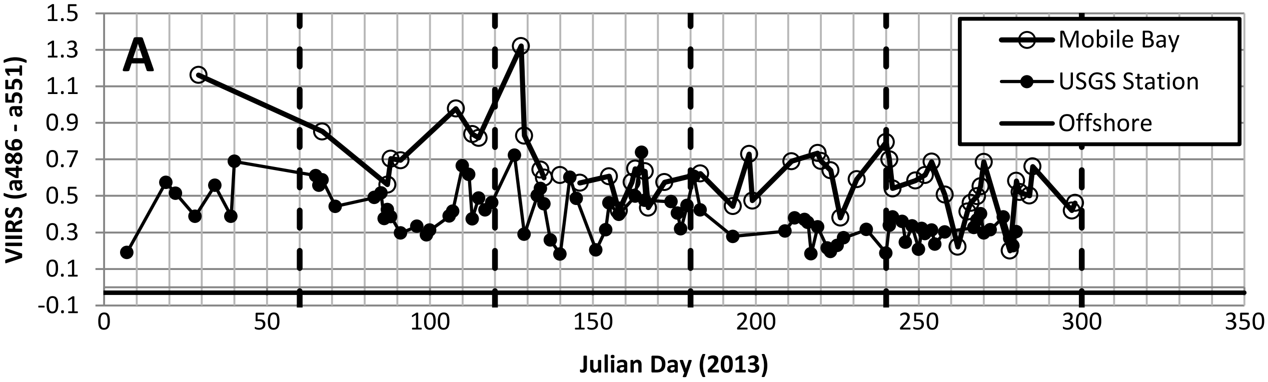


Figure 1. Google Earth Map projection of the Mississippi Sound and Bight, with stations used for algorithm development shown by the place markers (from left to right, USGS Site 301104089253400, 301429089145600, 301912088583300, 01527088521500, 301849088350000, NDBC station MLBA1). Closed circles indicate locations of *in situ* platforms used, while the dashed circle indicates the location of the satellite time series at the Mouth of the Mobile Bay.

3. APPROACH

The approach for this study was to matchup the VIIRS rrs and absorption products with *in situ* salinity retrievals to establish an empirical salinity algorithm. Previous studies have shown a direct relationship between salinity and chromophoric dissolved organic matter (CDOM)[6] in coastal waters, however the partitioning of other non-conservative constituents (absorption by detritus [ad] and phytoplankton [aph]) also absorbing blue light in case 2 waters is non-trivial, and can introduce additional uncertainty into the satellite retrievals[7]. Our approach minimized the stacking of complex algorithms by looking at rrs and total absorption, utilizing various linear (model I and II), non-linear, log-transformed, and multiple regression techniques to find the highest correlations between the satellite and *in situ* data. For this data set, the highest correlations were found in the difference between QAA absorption products (486 nm – 551 nm).

It is not expected that one regression model will describe the seasonal dynamics optimally, since the baseline (optical properties of freshwater at Mobile river mouth) is changing throughout the year relative to the test parameters (time-series at platforms; Figure 2a). We make the assumption that these changes in optical properties at the river mouth are not due to changes in salinity, but from changes in the water mass. For example, the concentration and spectral slope characteristics of CDOM can change considerably on varying time scales based on the amount of river discharge and the composition of CDOM (e.g. ratio of humic to fulvic acids[8]). Therefore, a time-series of satellite data (rrs and a_QAA) monitoring the mouth of local river inputs as well as case-1 oligotrophic waters can allow the normalization of data to important end members. Assuming the salinity values at river mouths (north Mobile Bay) range from 0 -3 psu, and open ocean oligotrophic waters are near 35 psu, bi-monthly regression slopes of salinity to optical signatures (a486 – a551) were determined by constraining bi-monthly averages of end members (river mouth and oligotrophic time series; Figure 2b). The amount of data added to the regression was a 0.2 factor of the sample size.



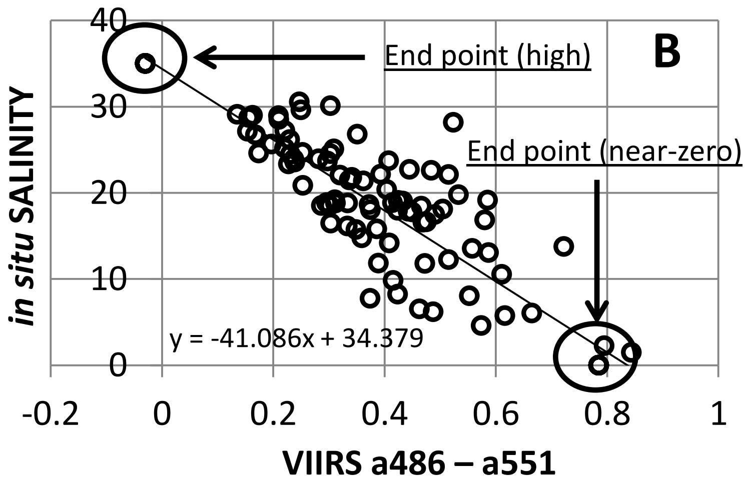


Figure 2. (A) Time-series of VIIRS absorption product (a486 – a551) retrievals for 2013. Differences between north Mobile Bay (assumed 0-3 psu), USGS station (301429089145600), and oligotrophic offshore waters illustrate the need to account for changes in optical properties that are independent of salinity. The vertical dotted lines show the bi-monthly partitions, over which mean values of river mouth and offshore water absorption products from VIIRS were obtained. (B) Scatter plot showing a two-month (Mar-Apr 2013) comparison of VIIRS absorption products to *in situ* salinity measurements derived from USGS and NDBC platforms. Two end members were added in (High = oligotrophic, Near-zero = Mobile Bay river mouth), determined from the average of satellite data obtained over the same time period.

4. RESULTS AND DISCUSSION

The approach described above was applied to all data in bi-monthly increments from January to October, 2013. Bi-monthly increments were selected in order to obtain enough data points to retrieve a confident slope, while maintaining enough partition to resolve seasonal signals. The equations for obtaining salinity from VIIRS absorption products (a486 – a551, QAA) for each bi-monthly time period are shown in Table 1.

Table 1: Bi-monthly equations for calculation of salinity (dependent variable) from remote sensing absorption product (a486 – a551; independent variable).

Months	**Equation**
Jan – Feb	$y = -38.295x + 34.423$
Mar – Apr	$y = -41.086x + 34.379$
May – Jun	$y = -46.113x + 34.673$
Jul – Aug	$y = -39.499x + 34.266$
Sep - Oct	$y = -44.531x + 34.035$

The equations were applied to the VIIRS data set and were evaluated using an *in situ* flow through data set (Figure 3b) in the Mississippi Sound/Mississippi Bight (see Figure 3 caption for cruise information). Figure 3a shows the algorithm applied to the Northern Gulf of Mexico, highlighting the area where the cruise track was for *in situ* validation. Results show good agreement of satellite data with *in situ* data among a range of salinity values.

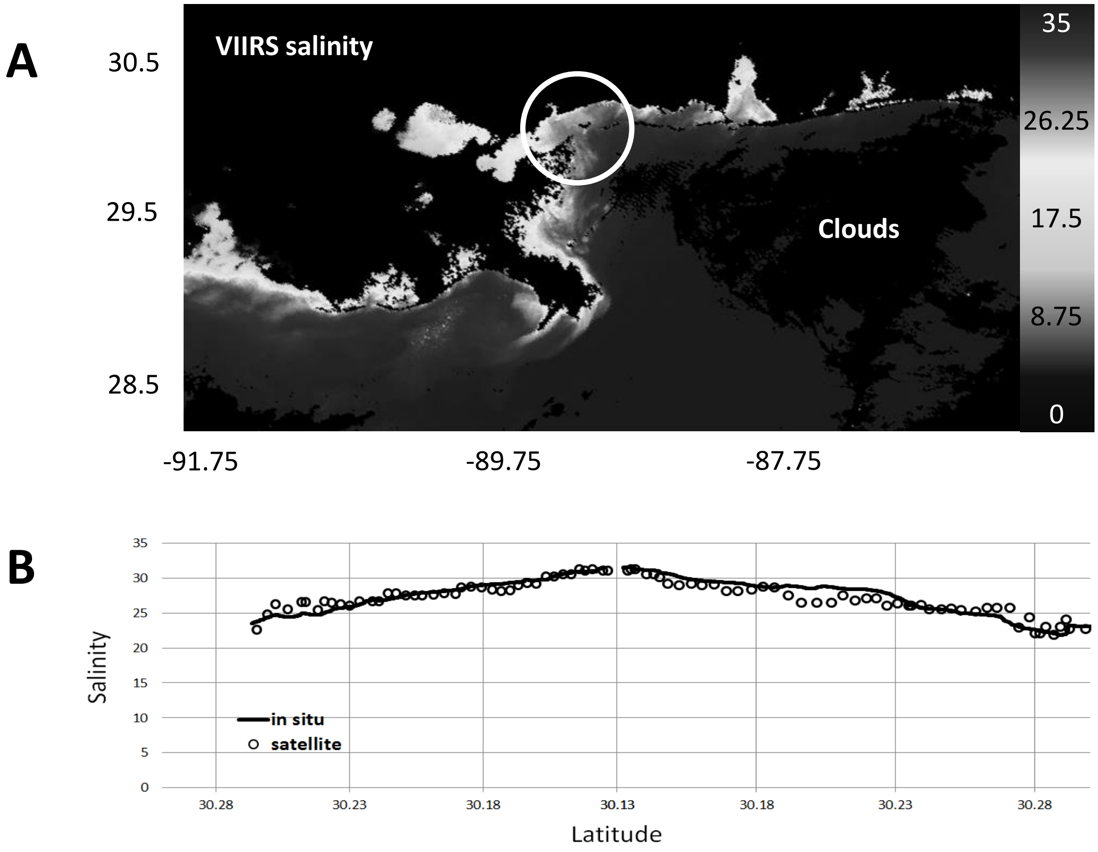


Figure 3. (A) VIIRS salinity image derived from absorption products. The white circle indicates the area where the flow through data set for *in situ* validation was collected. The image is from November 20, 2013, using the Sep-Oct equation in Table 1. (B) Spatial matchup of VIIRS-derived salinity with *in situ* flow through measurements, obtained from the Naval Research Laboratory cruise on the R/V Ocean Color (Nov 20, 2013, bound within 30.25 : 30.125, -89.325 : -89.025).

The qualitative analysis of errors in the salinity algorithm were derived from a complete data set of six stationary platforms, the afore mentioned flow through data set, as well as several offshore points obtained from a SeaGlider in the northern Gulf of Mexico (n = 419). For all data points, the absolute value of the difference between the *in situ* salinity and the VIIRS-derived salinity were obtained to see how well the model algorithm performed. These data were first sorted according to salinity range, and the median of the difference over 5 psu increments was calculated, along with the median absolute deviation (MAD; Figure 4a). The algorithm tends to have the highest uncertainty in the 5 – 10, and 15 – 20 psu range.

An evaluation of the percent error in the VIIRS SSS algorithms was performed by sorting the difference between the *in situ* data and the VIIRS-derived data (lowest to highest values). The purpose was to obtain a measurement of how many satellite values estimated the *in situ* value within a given error range. The analysis shows that 65% of the satellite data points were within 2 psu of the *in situ* measurement, while 90% of the satellite data points were within 5 psu of the *in situ* measurement (Figure 4b). Only about 10% of the satellite values were off by more than 5 psu.

The uncertainty present in the satellite algorithm is potentially multifaceted. First, considering the uncertainty in the coupling of optics with salinity, it is important to note that several processes may occur that can lead to a divergence of conservative mixing of optical properties from river water into the ocean, including photo-bleaching[9], adsorption onto sediment[10], flocculation[11], and biological production[12], though the effects of these processes vary with local conditions. In addition, the remote sensing reflectance signal does integrate a non-conservative scattering signal, which is likely why the absorption products, even with their inherent uncertainties from the QAA, had higher correlations.

The difference in the VIIRS absorption product (a486 nm – a551 nm) is a direct measure of the slope of the *total* absorption, however, the bulk of the signal is presumably due to the dominant absorption of CDOM/detritus, as phytoplankton absorption is generally minimal at 551 nm. If this is the case, low CDOM and high chlorophyll waters could potentially lead to a false salinity signal. Additional investigation and *in situ* validation of the underlying optical relationship is needed. A previous study in the Gulf of Mexico used the total absorption difference of 410 nm to 443 nm to determine salinity from SeaWiFS in a similar manner[13], however the reproduction of these results for VIIRS were unsuccessful, due to an apparent “striping” effect that manifested at lower wavelengths. Further resolution of the detector response aboard VIIRS may be necessary to use these wavelengths for VIIRS salinity retrievals.

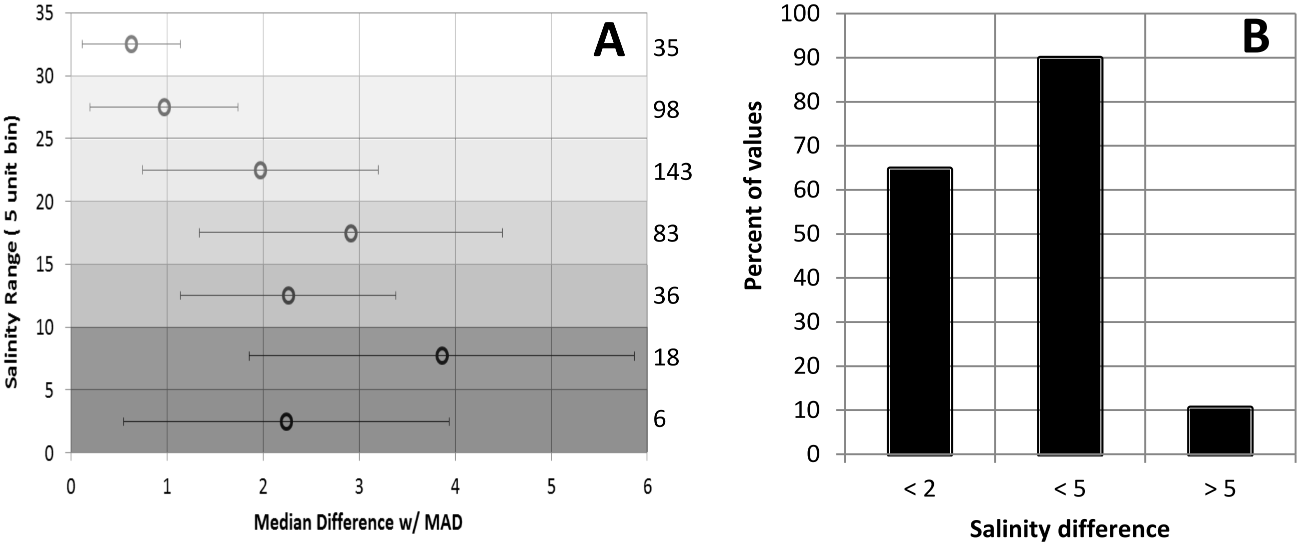


Figure 4. (A) The median absolute difference of the satellite salinity model from *in situ* salinity measurements for this study, partitioned by different salinity ranges (5 psu increments). The error bars represent the median absolute deviation for the sample size. The sample size is listed on the right side of the figure. (B) The percent of satellite values that estimated *in situ* values within a given threshold, showing that 90% of the satellite retrieved values were within 5 psu of observations.

5. PHYSICAL MODEL COMPARISON

Figure 5 shows a visual comparison between the VIIRS-derived surface salinity product, and that produced from the NAVY Coastal Ocean Model (NCOM[14]) for September 04, 2013. Both VIIRS and NCOM show the presence of large river plumes originating from the Mississippi Delta, however, some discrepancy exists between the locations of the plumes. The salinity values are relatively similar for the plumes as well, but VIIRS tends to produce significantly lower salinity values closer to shore (Mississippi Sound, Mobile Bay, Lake Pontchartrain, Chandeleur Sound) in relation to NCOM.

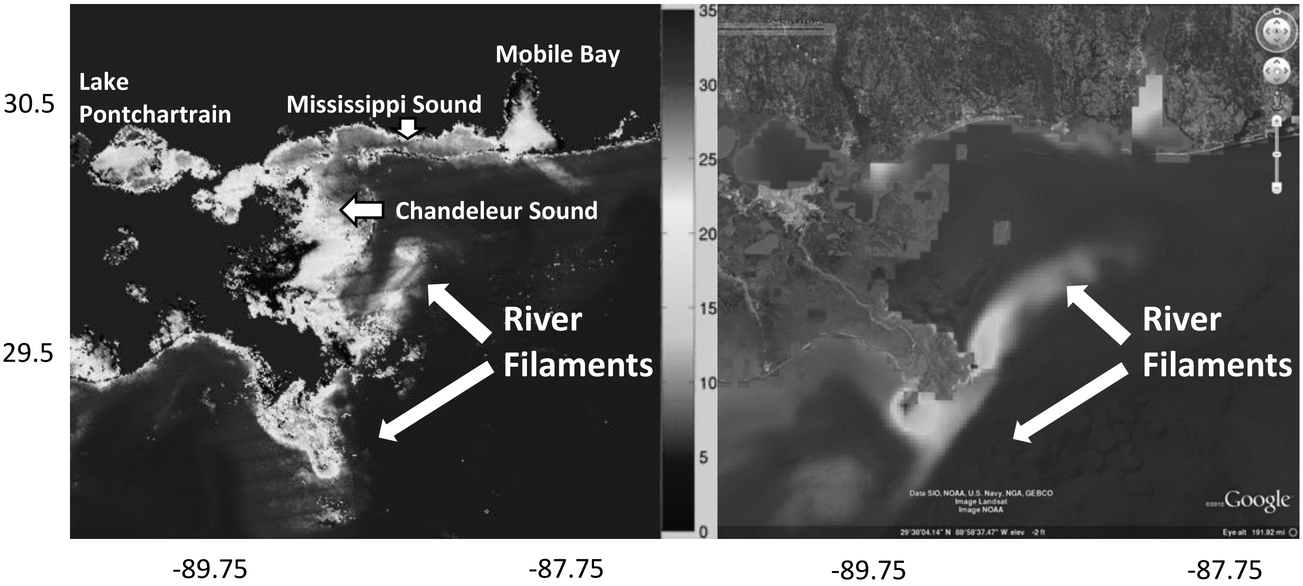


Figure 5. Comparison of VIIRS salinity product (left) with NCOM salinity product (right) on September 04, 2013. A pronounced river filament can be seen in both products, but there are larger differences in the near-coastal environment. The uncertainties of the physical circulation model are not discussed in this paper.

6. CONCLUSIONS

An empirical relationship derived from difference of the VIIRS total absorption (QAA) products (486 – 551 nm) was used to derive sea surface salinity estimates for the Northern Gulf of Mexico. *In situ* salinity data collected from six coastal moorings were compared to calibrated, geo-referenced satellite (SNPP-VIIRS) data at the same locations. A time-series of satellite absorption (QAA) products retrieved from the mouth of north Mobile Bay showed that baseline optical properties exhibit a seasonal signal. The derived empirical relationships between *in situ* salinity and satellite products were normalized to known “end points” (high and low salinity points) on a bi-monthly basis, to account for changes in optical properties associated with variations in river discharge and source material.

An independent flow through data set was used to validate the VIIRS salinity product, showing very close agreement along spatial gradients. Results also show that the surface salinity can be measured over time from satellite ocean color with 90% of the data falling within 5 psu of *in situ* values. Even with a higher inherent error than current microwave scatterometers, the high spatial (750-m) and temporal (daily) resolution obtained from ocean color sensors, in conjunction with the near real-time availability make the data extremely useful for decision-makers. It should be noted that this relationship is dependent on geographic location, but demonstrates a useful tool that can be derived, developed, and validated with open source data.

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