Adaptive ocean color algorithms for the estuarine-ocean continuum and assessment of optical-biogeochemical response to extreme events in nGoM

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Northern GoM estuarine-shelf system

- Understanding estuarine-coastal-ocean bio-geochemical processes is essential to improve:
  - carbon budgets
  - water quality monitoring

- Galveston Bay
- Barataria Bay
- Apalachicola Bay

- The diagram illustrates the estuarine-shelf system in the Northern Gulf of Mexico (GoM) with key locations marked:
  - Galveston Bay
  - Barataria Bay
  - Apalachicola Bay

- The system includes stations 1-17, and significant wetland loss is due to coastal level rise, waves, and subsidence.
nGoM Hot Spot of Extreme events

- Hurricanes are increasingly being recognized as important episodic drivers in coastal ocean biogeochemical cycling
  - 2005 (5 hurricanes); 2020 (8 hurricanes)

Hurricane Harvey – Aug. 25-29, 2017

Hurricane Michael - Oct. 10, 2018

Optical proxies for biogeochemical variables from ocean color (OC)
- CDOM absorption – Dissolved Organic Carbon (DOC)
- Backscattering coefficient – SPM, POC
- Phytoplankton absorption – biomass / taxonomy / size class
Outline

• Empirical OC algorithms – shelf & estuaries

• Tuning of the Quasi-analytical algorithm (QAA) as QAA-V for the optically complex and turbid estuarine waters and application

• Adaptive atmospheric correction

• Adaptive QAA (standard QAA + QAA-V) optimized for the estuarine-ocean continuum and application
Empirical ocean color algorithms for shelf waters

Suspended particulate matter (SPM) algorithm

From: D’Sa et al. 2006 – Applied Optics

CDOM algorithm

From: D’Sa et al. 2006 – Applied Optics

From: Tehrani et al. 2013 – Remote Sensing
Empirical algorithms for estuaries

CDOM/DOC trends in Barataria Bay using Landsat/MODIS (1985-2012)

From: Liu, D’Sa & Joshi 2019-RSE
Long-term trends in DOC concentrations in Barataria Bay using Landsat/MODIS data and linkages to LULC change

From: Liu, D’Sa & Joshi 2019-RSE
Apalachicola Bay: Seasonal CDOM/DOC stocks and fluxes using VIIRS & NCOM measurement) at each sampling station. Glint and residual corrections were applied on raw radiance measurements as suggested by Gould et al. (2001). The level-L1B VIIRS (Visible Infrared Imaging Radiometer Suite) imagery (Sensor Data Record-SDR product) was downloaded from NASA's Ocean Color website, and processed using SeaDAS 7.3 (OBGP, NASA).

Radiometrically-calibrated VIIRS imagery was converted into the CDOM absorption coefficient $a_{412}$ and DOC concentration maps using two pathways (Fig. 2): 1) evaluating and applying a suitable atmospheric-correction scheme to the VIIRS imagery in an optically complex coastal system, and 2) developing empirical relationships between atmospherically-corrected $R_{rs}$ and $a_{412}$, and subsequently to DOC concentration to convert the VIIRS imagery into the $a_{412}$ and DOC maps for Apalachicola Bay.

2.3. Absorption spectroscopy

Absorbance (A) spectra were measured on a Perkin Elmer Lambda-850 double beam spectrophotometer equipped with a 150 mm-integrating sphere. Following the instrument warm up and equilibration of samples to room temperature, absorbance spectra were obtained between 250 and 750 nm at 1-nm intervals using 10-cm path length quartz cuvette. The cuvette was rinsed twice with ultrapure water (a Thermo Scientific Micro-Pure UV purification system with a purity of 18.2 MΩ) and once with filtered seawater before each measurement to avoid contamination by the previous sample. Absorption coefficients ($a_{\lambda}$) were calculated using the following equation,

$$a_{\lambda} = \frac{2.303}{C_2} \frac{A_{\lambda}}{L}$$

where, $A_{\lambda}$ is absorbance at a wavelength $\lambda$, and $L$ is pathlength in meters. The absorption spectra were corrected for scattering, temperature, and baseline drift by subtracting a value of absorption at 750 nm from each spectrum (Green and Blough, 1994). Wavelength-dependent exponential decay of the absorption coefficient can be given by the following non-linear equation,

$$a_{\lambda} = a_{\lambda ref} / C_0 / C_1 e^{-S_{\lambda ref} - \lambda}$$

where, $a_{\lambda}$ is the amplitude of the CDOM absorption coefficient at any wavelength $\lambda$, and $\lambda_{ref}$ is the reference wavelength (Jerlov, 1976; Shifrin, 1988). The absorption spectra generally represented by a non-linear equation (Eq. (2)), were converted to a linear form by a logarithmic transformation of dependent variable. Then, a least squares regression approach was applied to calculate spectral slope $S_{275-295}$ between 275 nm and 295 nm, while absorption coefficient at 412 nm ($a_{412}$) was used as a quantitative parameter of the CDOM (D'Sa et al., 2006; D'Sa et al., 2014).

A VIIRS-based CDOM algorithm

NCOM Hydrodynamic model-current & salinity
Hurricane Harvey impact on Galveston Bay
carbon distribution & fluxes

- Hurricane Harvey (25-29 Aug, 2017) dumped record rainfall in the Houston and surrounding region (>52”)

Need:
- Critical to monitor short- and long-term response of water quality constituents – NASA Rapid Response

Challenges:
- Estuarine waters are optically complex and limitations of standard ocean color algorithms including semi-analytical
  
- apply/tune semi-analytic algorithm such as QAA  (Lee et al. 2002)

NASA imagery on 31st August 2017
Data for tuning the QAA and carbon flux studies

• Field surveys conducted in Galveston Bay, Apalachicola Bay and Barataria Bay

• Surface water samples were collected for absorption (CDOM, phytoplankton, non-algal particles), DOC, phytoplankton pigments, and SPM concentrations

• Bio-optical package comprising a suite of instruments including: CTD, Wetlabs eco-triplet (chlorophyll, CDOM fluorescence, and backscattering at 532 nm), ACS

• Remote sensing reflectance $R_{rs}$ (GER 1500 512iHR spectroradiometer)

• Synthetic data from Hydrolight simulation

• NOMAD dataset
Tuning of the QAA for turbid estuaries as (QAA-V); 2 major changes

(1) The coefficients $g_0$ and $g_1$ of a SAA quadratic relationship were updated to obtain $u$ from the $R_{rs}$

$$u(\lambda) = \frac{-g_0 + [g_0^2 + 4 \times g_1 \times R_{rs}^{0-}(\lambda)]^{0.5}}{2 \times g_1}$$

$$\rho = \log_{10} \left( \frac{R_{rs}^{0-}(\lambda_0)}{R_{rs}^{0-}(671)} \right)$$

$g_0 = 0.0788$ and $g_1 = 0.2379$ for $\rho < 0.25$

$g_0 = 0.0895$ and $g_1 = 0.1247$ for $\rho \geq 0.25$

From: Joshi & D’Sa 2018-Biogeosciences
(2) A threshold-based empirical model was proposed using the G/R band ratio to estimate the total absorption coefficient at a reference wavelength.

(3) Calibration coefficients for sensor-specific QAA tuning: VIIRS, MODIS-Aqua, Sentinel-3 OLCI, MERIS, SeaWiFS, Sentinel-2 MSI, Landsat 8 OLI.
Validation of QAA-V and performance comparison to QAA-v6

- Validation of total absorption coefficient for estuarine & nearshore field data

- Statistical assessment of QAA-V vs QAA-V6

- QAA-V showed obvious improvements over QAA-v6 with ~30-40% reduction in absolute mean relative error for Hydrolight simulated synthetic and in situ estuarine datasets

Joshi & D’Sa 2018-BGS
Application: QAA-V in Galveston Bay

VIIRS Remote Sensing Reflectance Rrs (downloaded from NASA OC site)

VIIRS Rrs (atmospheric correction)

QAA-V PROCESSING CHAIN
Lee et al. 2002
Joshi & D’Sa-2018

Outputs (validation)
absorption coefficients
scattering coefficients

Relationship between $b_{bp}(532)$ vs SPM (mg/L) for Galveston Bay
(29 Sep, 29 & 30 Oct 2017)
Optical property (backscattering coefficient) to SPM

SPM MAPS

major factors influencing
-River discharge
-wind forcing
-re-suspension
-shelf transport

SPM dynamics following Hurricane Harvey

Joshi & D’Sa 2018-Biogeosciences
Coastal ocean optical-geochemical response to Hurricane Harvey

- Flowchart showing processing approach for obtaining VIIRS estimates of DOC and POC in Galveston Bay

From: D’Sa, Joshi and Liu 2018-GRL
POC dynamics following Hurricane Harvey in Galveston Bay

\[ SPM = 103.07 \times b_{bp532} + 0.24 \]

\[ POC^* = 725.60 \times SPM^{-0.701} \]

where \( POC^* = \frac{POC}{SPM} \).


D’Sa, Joshi and Liu 2018-GRL
CDOM/DOC dynamics following Hurricane Harvey
Volume, DOC, POC fluxes linked to Hurricane Harvey

D’Sa, Joshi and Liu 2018-GRL

- Top: water level and surface currents at Galveston Bay entrance
- Bottom: TR+SJR discharge; +volume flux at entrance; DOC & POC fluxes

- Over 10 days during/following hurricane, ~25x10^6 kg C (TOC) and ~314x10^6 kg of SPM were rapidly exported from GB to shelf
Atmospheric correction (ATCOR) in estuarine-shelf waters

\[ L_T (\lambda) = L_{ATM} (\lambda) + L_{SURF} (\lambda) + t_d L_w (\lambda) \]

\[ R_{rs} = L_w (\lambda) / E_d (\lambda) \]

- We use ATCOR algorithms readily available in NASA’s SeaDAS software that are variants of the basic Gordon and Wang (1994) that assumes black pixel; these variants make adjustment to the non-negligible NIR radiance

- Iterative NIR (Bailey et al 2010; BFW10): works well in productive shelf and open ocean

- MUMM NIR scheme (Ruddick et al. 2000; R00) good for moderately turbid sediment-rich waters

- SWIR approach (Wang and Shi 2007; WS05) Works well in highly turbid waters

- To utilize the strengths of three well know NIR and SWIR correction algorithms we propose a methodology for a pixel-by-pixel selection of correction algorithms based on spectral criteria of different water types and for further blending two QAAs: QAA-v5 and QAA-V for the MODIS-Aqua
Adaptive atmospheric correction algorithms (AD-ATCOR; MODIS-Aqua)

Fig. 4. Different water types in a MODIS-Aqua scene (December 13, 2012) collected over the nGoM. (a) Rrs spectra over the green water. (b) Rrs spectra over the blue water. (c) Rrs spectra over the brown water. (d) Rrs spectra corresponding to the bright blue waters likely due to coccolithophores. Colored lines represent an average of all spectra.

From: Joshi & D’Sa 2020-IEEE TGRS
Adaptive atmospheric correction algorithms (AD-ATCOR; MODIS-Aqua)

From: Joshi & D’Sa 2020-IEEE TGRS

• The process begins with the BFW10-corrected image and the pixels will be replaced with the corresponding pixels in the R00 and WS05-corrected images based on the spectral criteria.
Performance of AD-ATCOR

Joshi & D’Sa 2020-IEEE TGRS

Fig. 7. Maps showing pixel-by-pixel application of three correction algorithms, BFW10 (blue), R00 (green), and WS05 (red), in heterogeneous waters of nGoM during (a) normal condition (May 6, 2017), (b) MR flood (April 13, 2008), (c) MR drought (October 19, 2012), and (d) passage of a cold front (February 26, 2016). A polygon (cyan color) shows bright water pixels likely due to Coccolithophores (condition-3 in Fig. 2).
Adaptive QAA (AD-QAA: QAA-V or QAA-v5)

Joshi & D’Sa 2020-IEEE TGRS

Limitations of QAA-V – optimized for estuaries
Limitations of QAA-v5 – works well in ocean/coastal waters
Adaptive QAA (AD-QAA: QAA-V & QAA-v5)

From: Joshi & D’Sa 2020 IEEE TGRS

Fig. 9. MODIS-Aqua Rho (ρ) maps showing pixel-by-pixel application (AD-QAA) of two QAAs algorithms, QAA-V and QAA-v5, using ρ thresholds (step-5 in Fig. 2) in heterogeneous waters of nGoM during four conditions. (a) Normal condition (May 6, 2017). (b) MR flood (April 13, 2008). (c) MR drought (October 19, 2012). (d) Passage of a cold front (February 26, 2016).
AD-QAA: total absorption coefficients

Joshi & D’Sa 2020-IEEE TGRS
AD-QAA: backscattering coefficients
Application: Hurricane Michael impact (Oct 10, 2018) using MODIS Aqua
POC and DOC maps in Apalachicola Bay

D’Sa et al. 2019-Frontiers Marine Science
Hurricane Michael: DOC and POC distribution and fluxes

NCOM hydrodynamic model

- Average flux of organic carbon exported between 5-21 Oct were much greater for DOC ($0.86 \times 10^6$ kg C d$^{-1}$) than POC ($0.21 \times 10^6$ kg C d$^{-1}$)

Fluxes of DOC and POC

D’Sa et al. 2019-FMS
Summary

- Estuarine-ocean continuum in nGoM include highly turbid and optically complex to clear oligotrophic waters within a satellite scene. Adaptive atmospheric correction and QAA offer advantage in processing ocean color – recent study (Liu et al. 2021 – RSE) used adaptive QAA for Sentinel-3 OLCI to retrieve phytoplankton absorption; further used to retrieve phytoplankton size structure

- Optical proxies (absorption and scattering coefficients) of biogeochemical variables derived using adaptive QAA could support water quality monitoring and biogeochemical modeling in the coastal ocean

- Obtaining field optical/biogeochemical data critical in characterizing the various estuarine systems

- With increase in TCs, flooding, storm surges, in nGoM there is need for collaborative efforts to address coastal impacts associated with these episodic events