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

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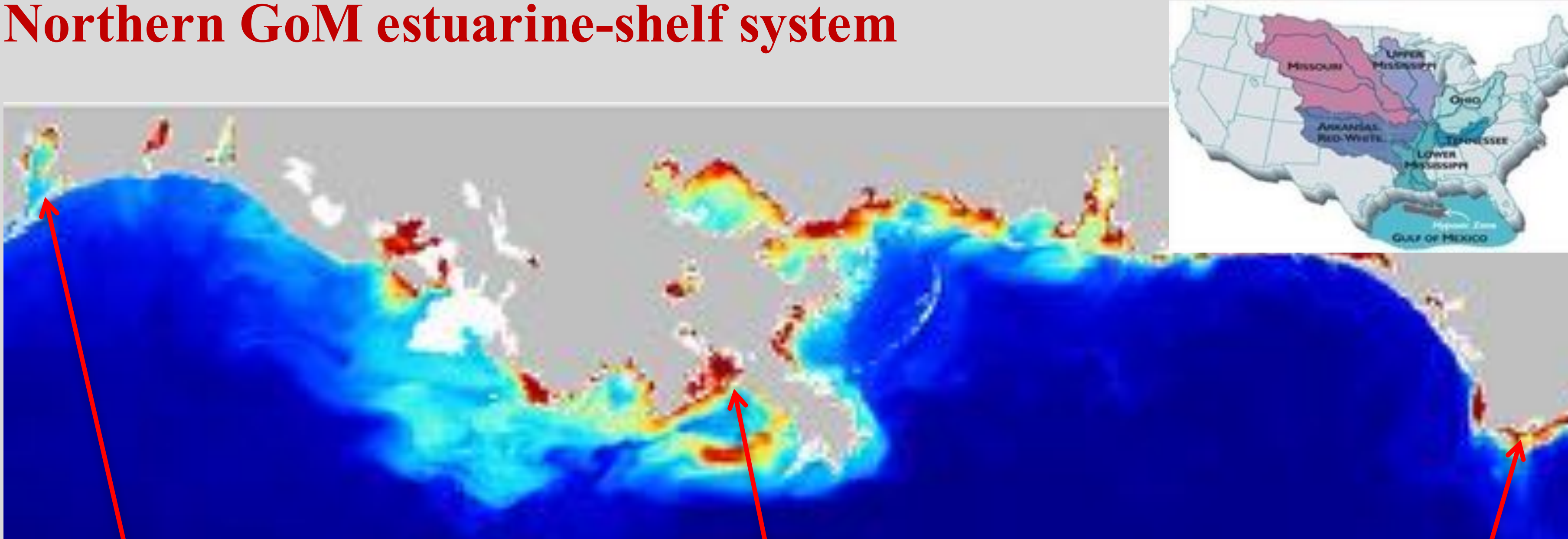
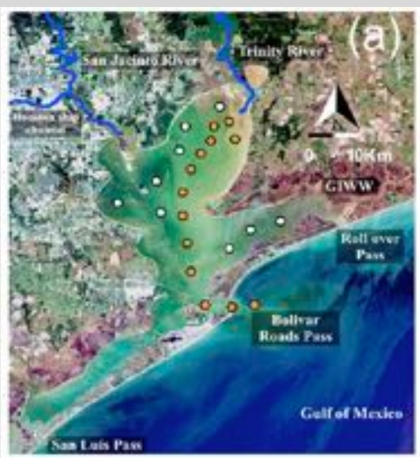
Northern GoM estuarine-shelf system

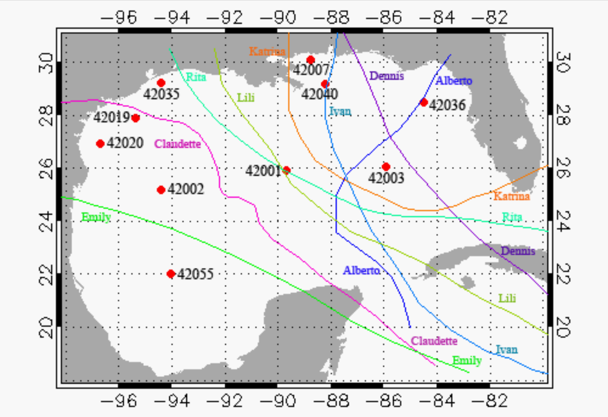


- Galveston Bay
- Barataria Bay
- Apalachicola Bay



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

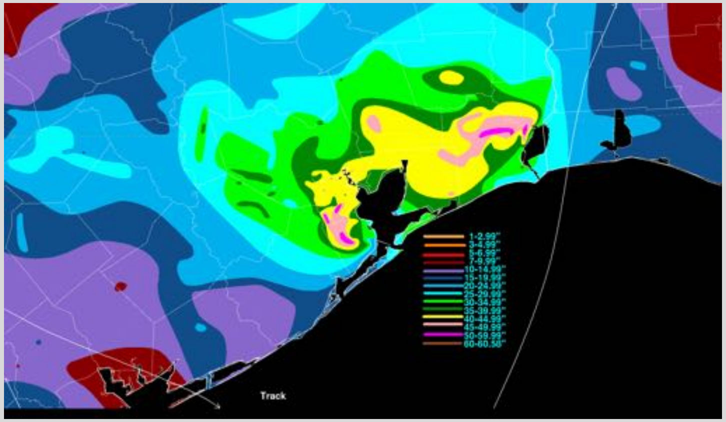
nGoM Hot Spot of Extreme events



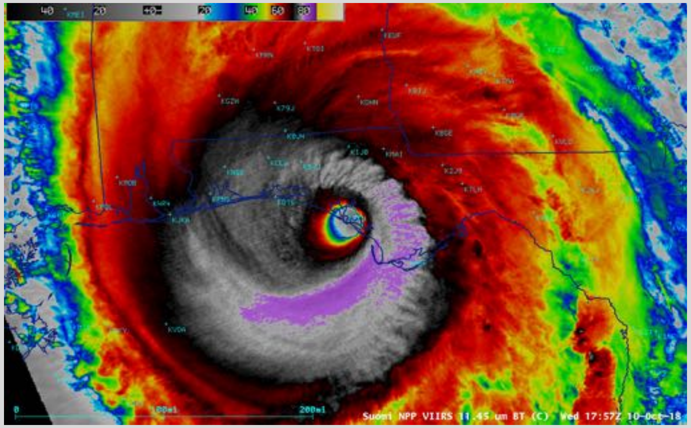
•Hurricanes are increasingly being recognized as important episodic drivers in coastal ocean biogeochemical cycling

•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

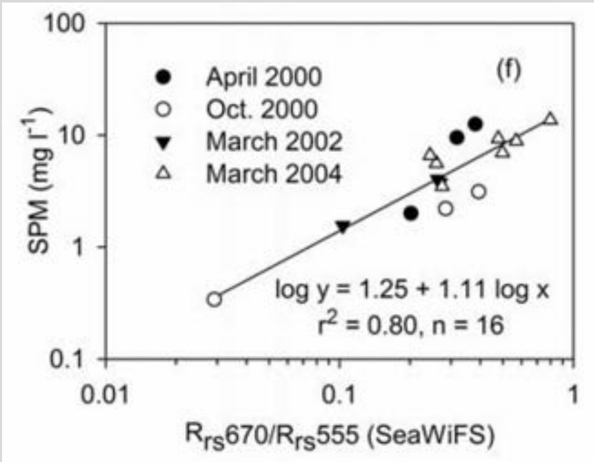
•Tuning of the Quasi-analytical algorithm (QAA) as QAA-V for the optically complex and turbid estuarine waters and application

•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



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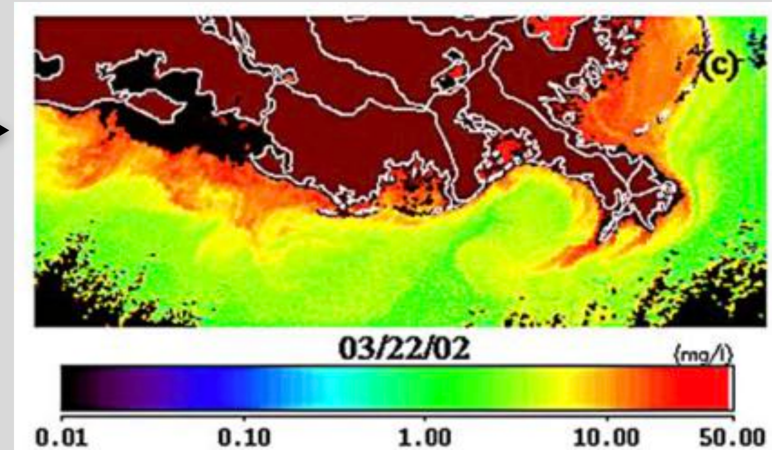
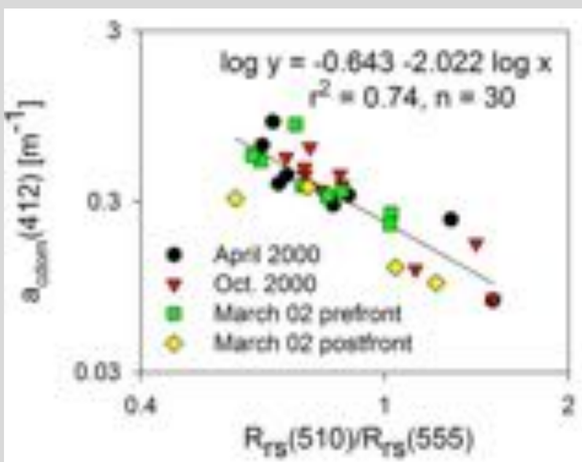


From: D'Sa et al. 2007 – GRL

CDOM algorithm



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

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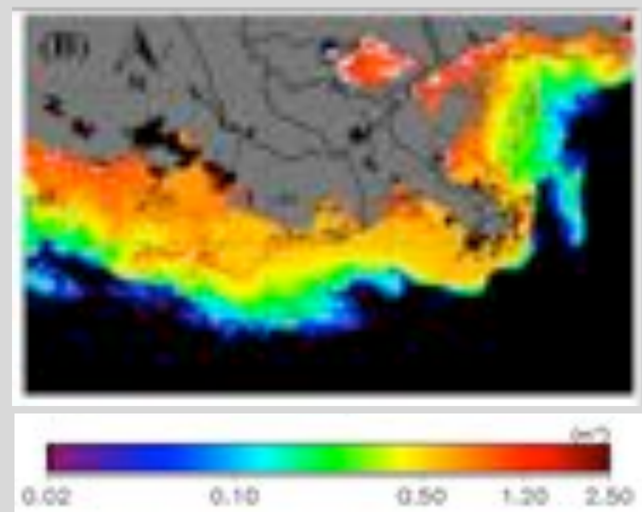
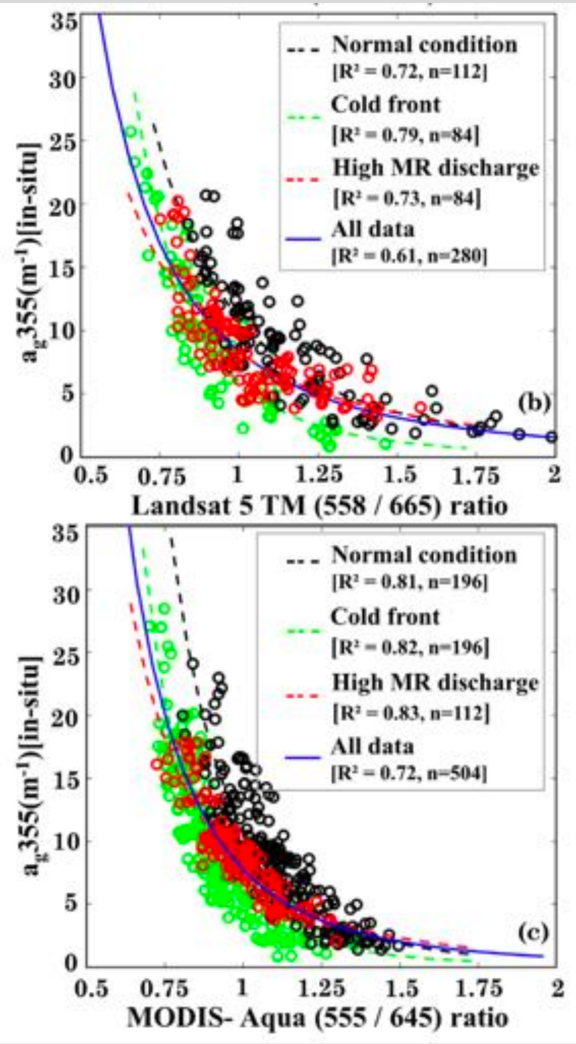
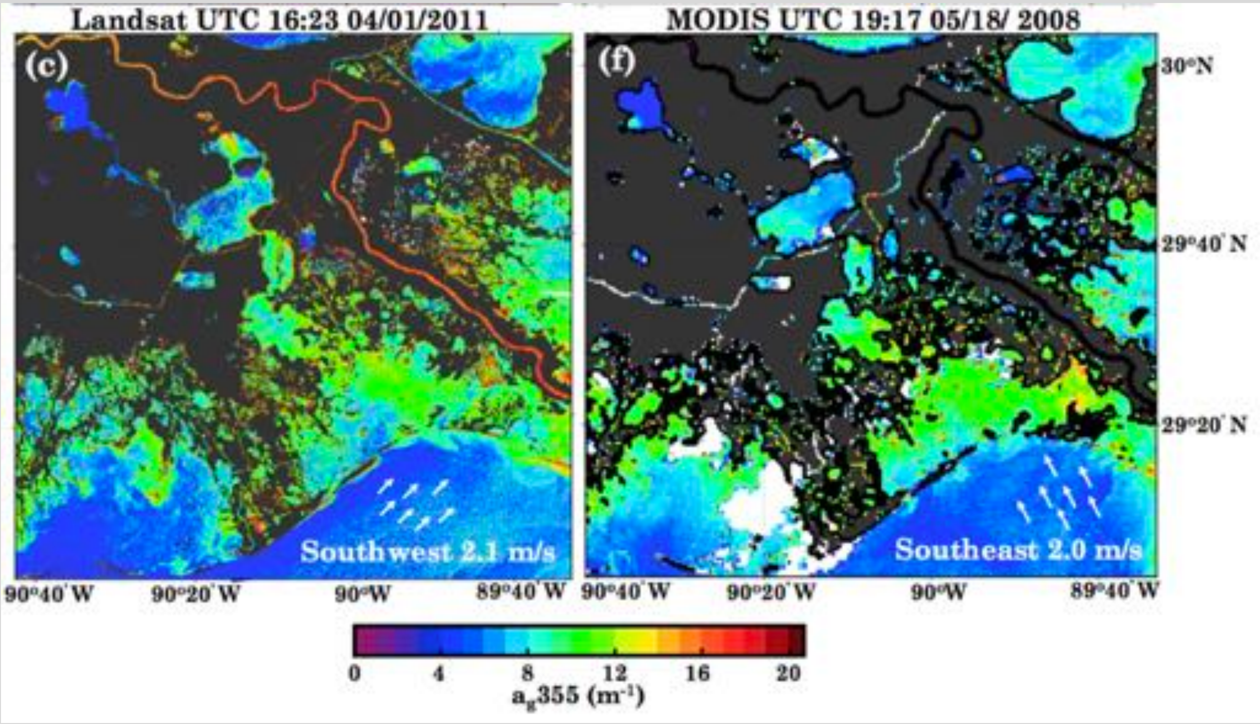


From: Tehrani et al 2013 – Remote Sensing

Empirical algorithms for estuaries

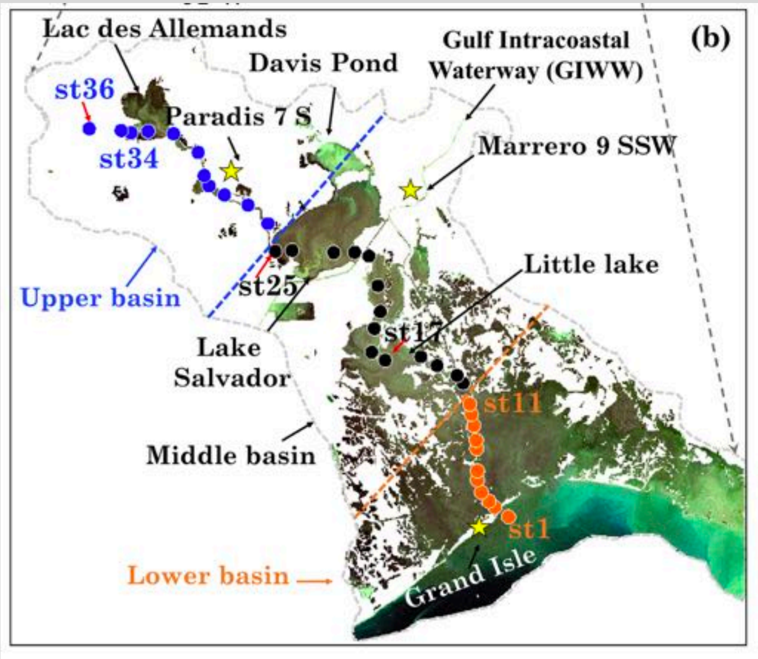


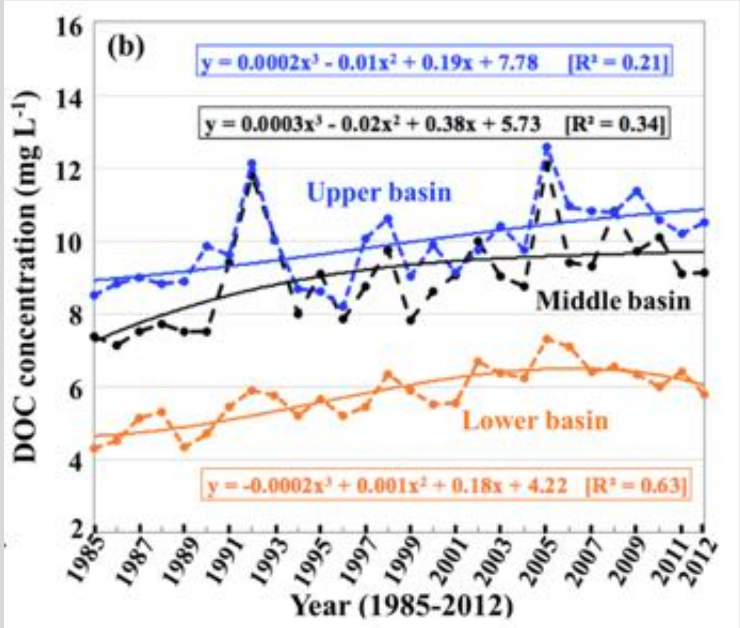
CDOM/DOC trends in Barataria Bay using Landsat/MODIS (1985-2012)



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

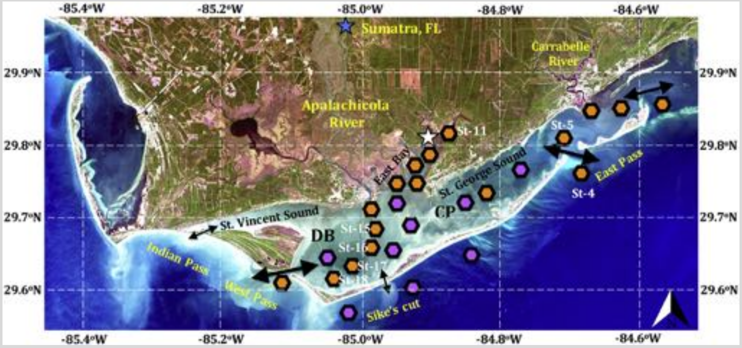


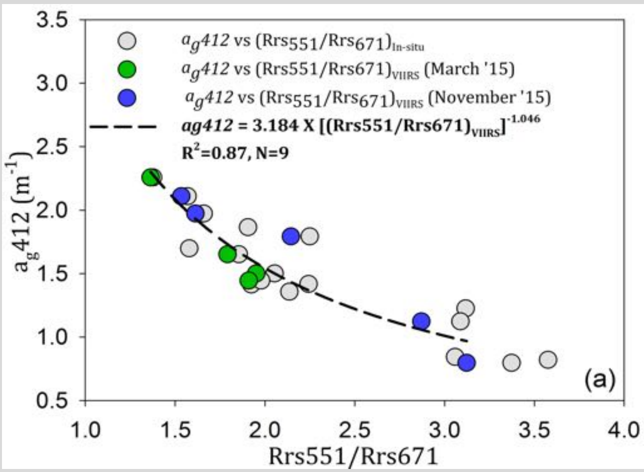


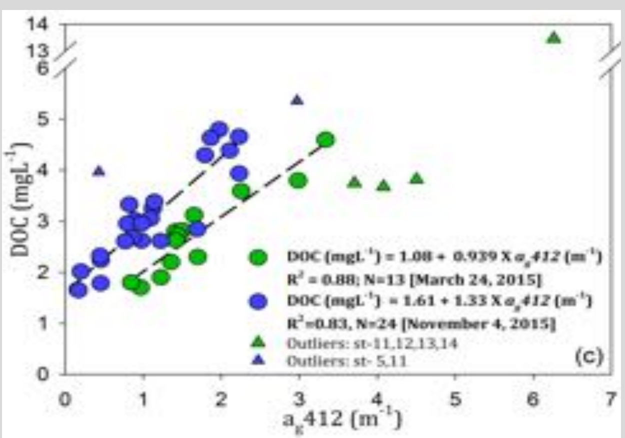
From: Liu, D’Sa & Joshi 2019-RSE

Apalachicola Bay: Seasonal CDOM/DOC stocks and fluxes using VIIRS & NCOM

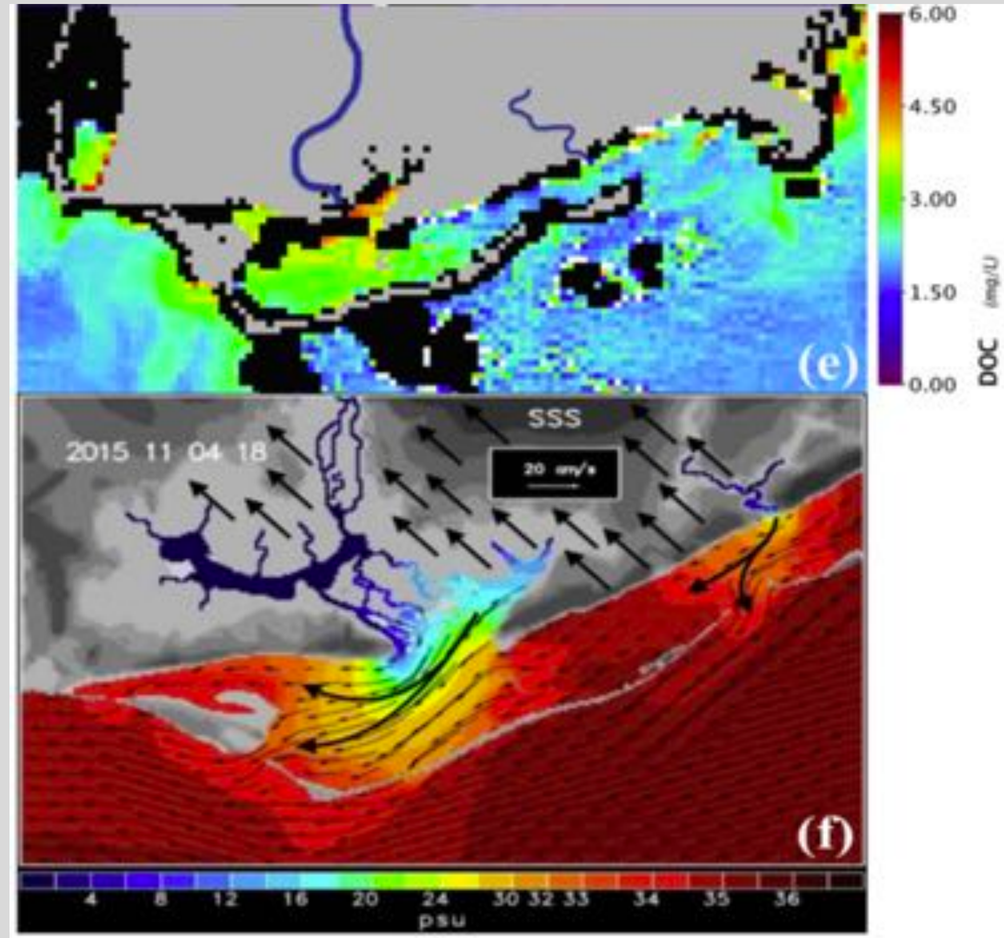
Joshi et al. 2017, Remote Sens. Environ.







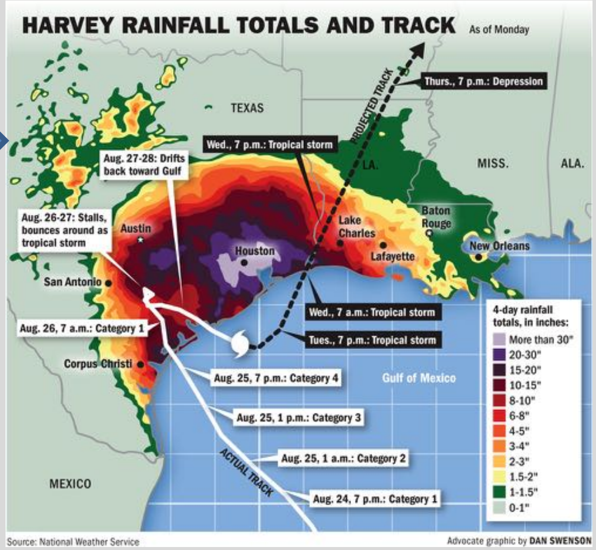
A VIIRS-based CDOM algorithm



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

NASA imagery on 31st August 2017

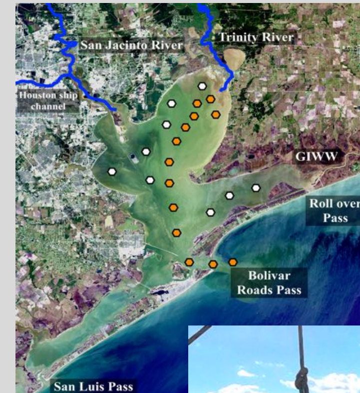
Challenges:

•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)

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

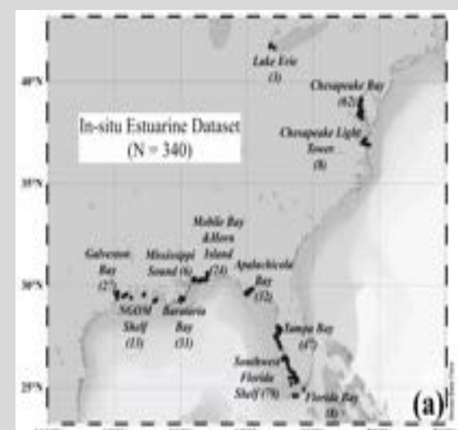
- Bio-optical package comprising a suite of instruments including: CTD, Wetlabs eco-triplet (chlorophyll, CDOM fluorescence, and backscattering at 532 nm), ACS

Bio-optical Profiler

- 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

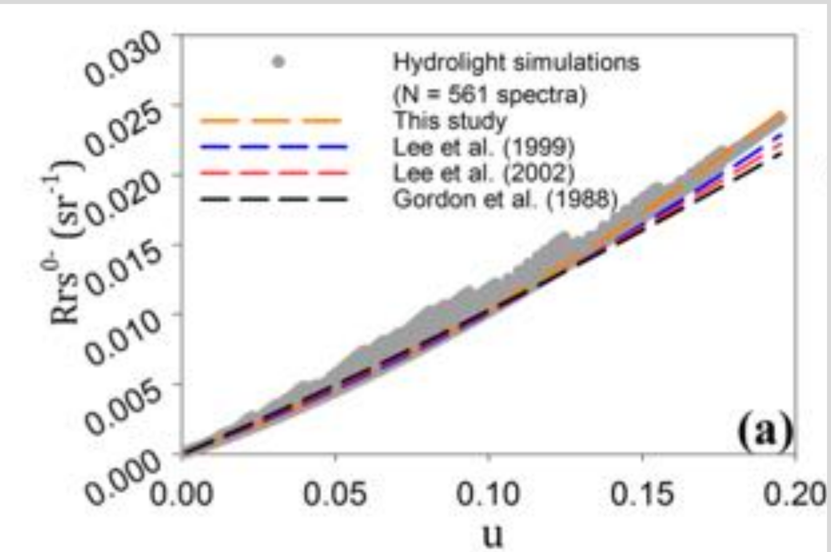
(1) The coefficients g_0 and g_1 of a SAA quadratic relationship were updated to obtain u from the R_{rs}

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

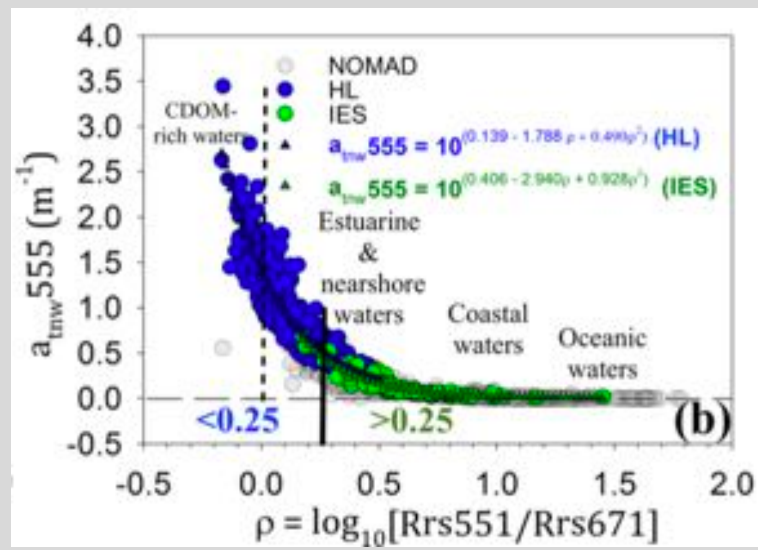
$$\rho = \log_{10}\left(\frac{R_{rs}^{0-}(\lambda_0)}{R_{rs}^{0-}(671)}\right)$$

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

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



$$u\,(= b_b/(a + b_b)) \text{ vs. } R_{rs}^{0-}$$



From: Joshi & D’Sa 2018-Biogeosciences

Tuning the QAA (Lee et al. 2002) for estuarine waters (QAA-V)

Level	Parameter	Model	Type
0	$R_{rs}{}^{0-}(\lambda)$	$R_{rs}{}^{0-}(\lambda) = \frac{R_{rs}{}^{0+}(\lambda)}{0.52 + 0.17 \times R_{rs}{}^{0+}(\lambda)}$	Semi-analytical
1A	$u(\lambda)$	$u(\lambda) = \frac{-g_0 + [g_0^2 + 4 \times g_1 \times R_{rs}{}^{0-}(\lambda)]^{0.5}}{2 \times g_1}$ $\rho = \log_{10}\left(\frac{R_{rs}{}^{0-}(\lambda_0)}{R_{rs}{}^{0-}(671)}\right)$ $g_0 = 0.0788$ and $g_1 = 0.2379$ for $\rho < 0.25$ $g_0 = 0.0895$ and $g_1 = 0.1247$ for $\rho \geq 0.25$	Semi-analytical
1B	$a_{tnw}(\lambda_0)$ $\lambda_0 = 551$ or 555	$a_{tnw}(\lambda_0) = \begin{cases} 10^{(0.139-1.788\times\rho+0.490\times\rho^2)} \text{ if } \rho < 0.25 \\ 10^{(0.406-2.940\times\rho+0.928\times\rho^2)} \text{ if } \rho \geq 0.25 \end{cases}$ $\rho = \log_{10}\left(\frac{R_{rs}{}^{0-}(\lambda_0)}{R_{rs}{}^{0-}(671)}\right)$	E
1C 0	$b_{b_{tnw}}(\lambda_0)$	$b_{b_{tnw}}(\lambda_0) = \frac{(a_{tnw}(\lambda_0) + a_w(\lambda_0)) \times u(\lambda_0)}{1 - u(\lambda_0)} - b_{b_w}(\lambda_0)$	Analytical
1	η	$\eta = -0.566 + \log_{10}(b_{btnw}555)$	Empirical
2	$b_{b_t}(\lambda)$	$b_{b_t}(\lambda) = b_{b_w}(\lambda) + b_{b_{tnw}}(\lambda_0) \times \left(\frac{\lambda_0}{\lambda}\right)^{\eta}$	Semi-analytical
3	$a_t(\lambda)$	$a_t(\lambda) = b_{b_t}(\lambda) \times \left(\frac{1-u(\lambda)}{u(\lambda)}\right)$	Analytical
SPM models			
This study		$SPM = (103.07 \times b_{b_{tnw}}532) + 0.24$	Empirical
D'Sa et al. (2007)		$SPM = (106.93 \times b_{b_{tnw}}555) + 0.61$	Empirical
Nechad et al. (2010)		$SPM = \left(\frac{A^{\rho} \times \rho_w}{1 - \rho_w / C^{\rho}}\right) + B^{\rho}$; where A^{ρ}=373.79 mg L^{-1}, B^{ρ}=1.47 mg L^{-1}, C^{ρ}= 0.1747 for λ=670 nm	Empirical

QAA-V processing chain

(2) a threshold-based empirical model was proposed using the G/R band ratio to estimate the total absorption coefficient at a reference wavelength

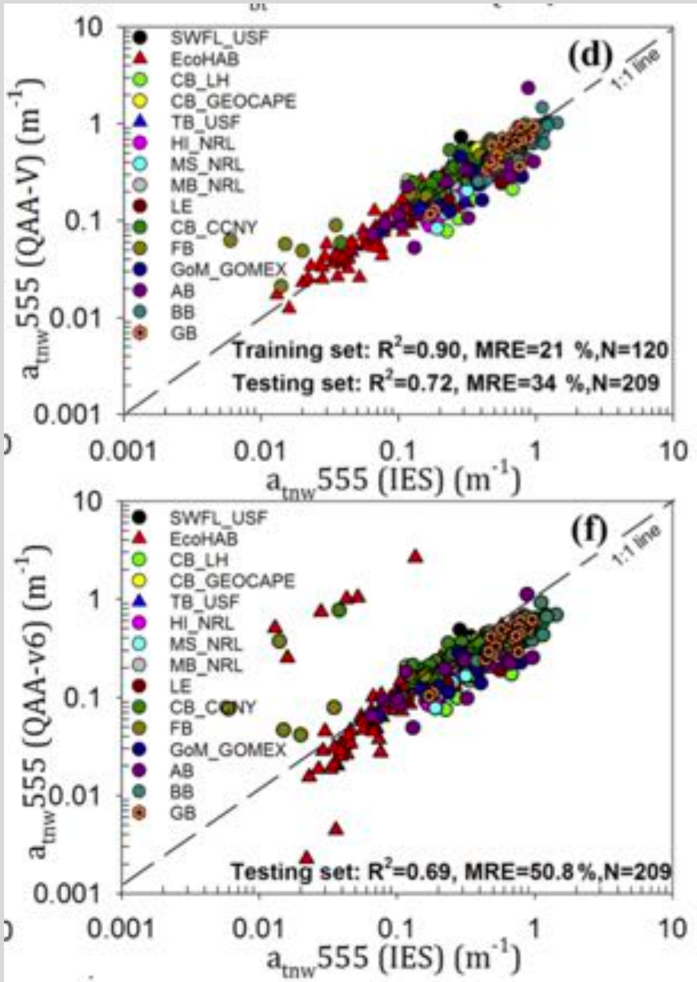
$$a_{tnw}(\lambda_0) = \begin{cases} 10^{(0.139-1.788\times\rho+0.490\times\rho^2)} & \text{if } \rho < 0.25 \\ 10^{(0.406-2.940\times\rho+0.928\times\rho^2)} & \text{if } \rho \geq 0.25 \end{cases}$$

$$\rho = \log_{10}\left(\frac{R_{rs}^{0-}(\lambda_0)}{R_{rs}^{0-}(\lambda_1)}\right)$$

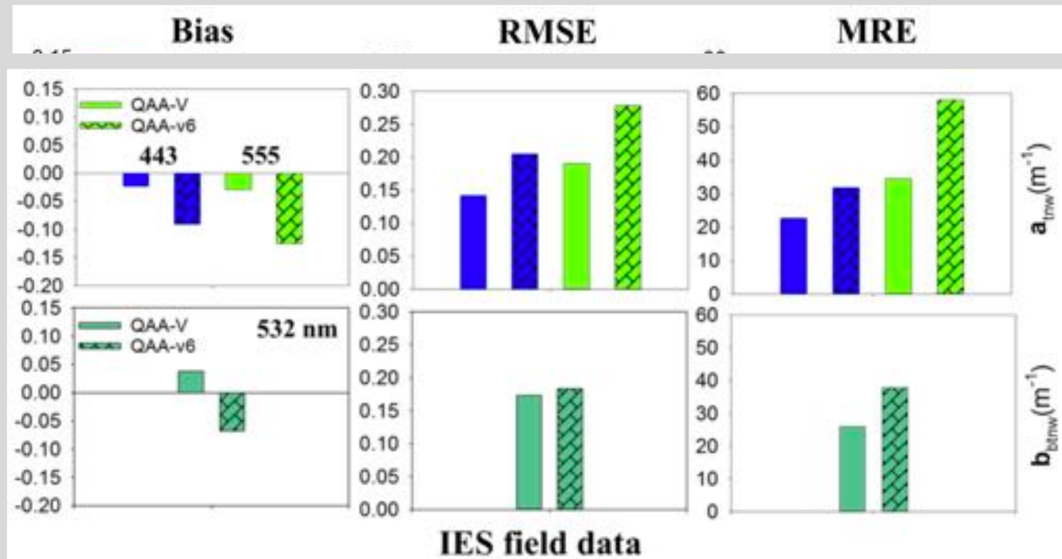
(3) Calibration coefficients for sensor-specific QAA tuning: VIIRS, MODIS-Aqua, Sentinel-3 OLCI, MERIS, SeaWiFS, Sentinel-2 MSI, Landsat 8 OLI

Joshi & D'Sa 2018-Biogeosciences

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

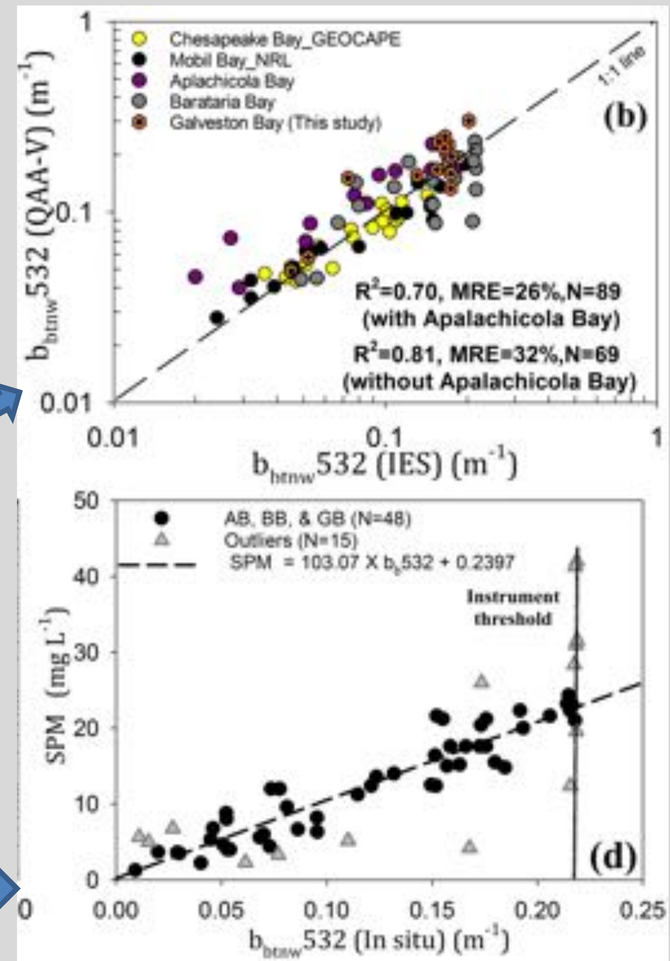
VIIRS Remote Sensing Reflectance Rrs (downloaded from NASA OC site)

VIIRS Rrs (atmospheric correction)

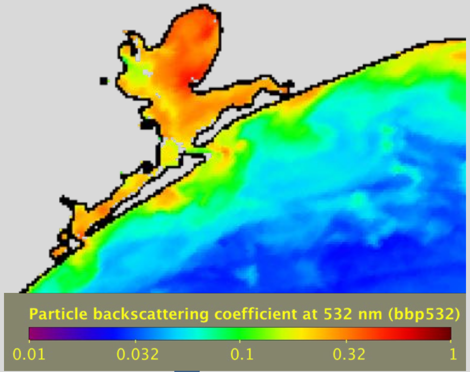
QAA-V PROCESSING CHAIN
Lee et al. 2002
Joshi & D'Sa-2018

Outputs (validation)
absorption coefficients
scattering coefficients

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

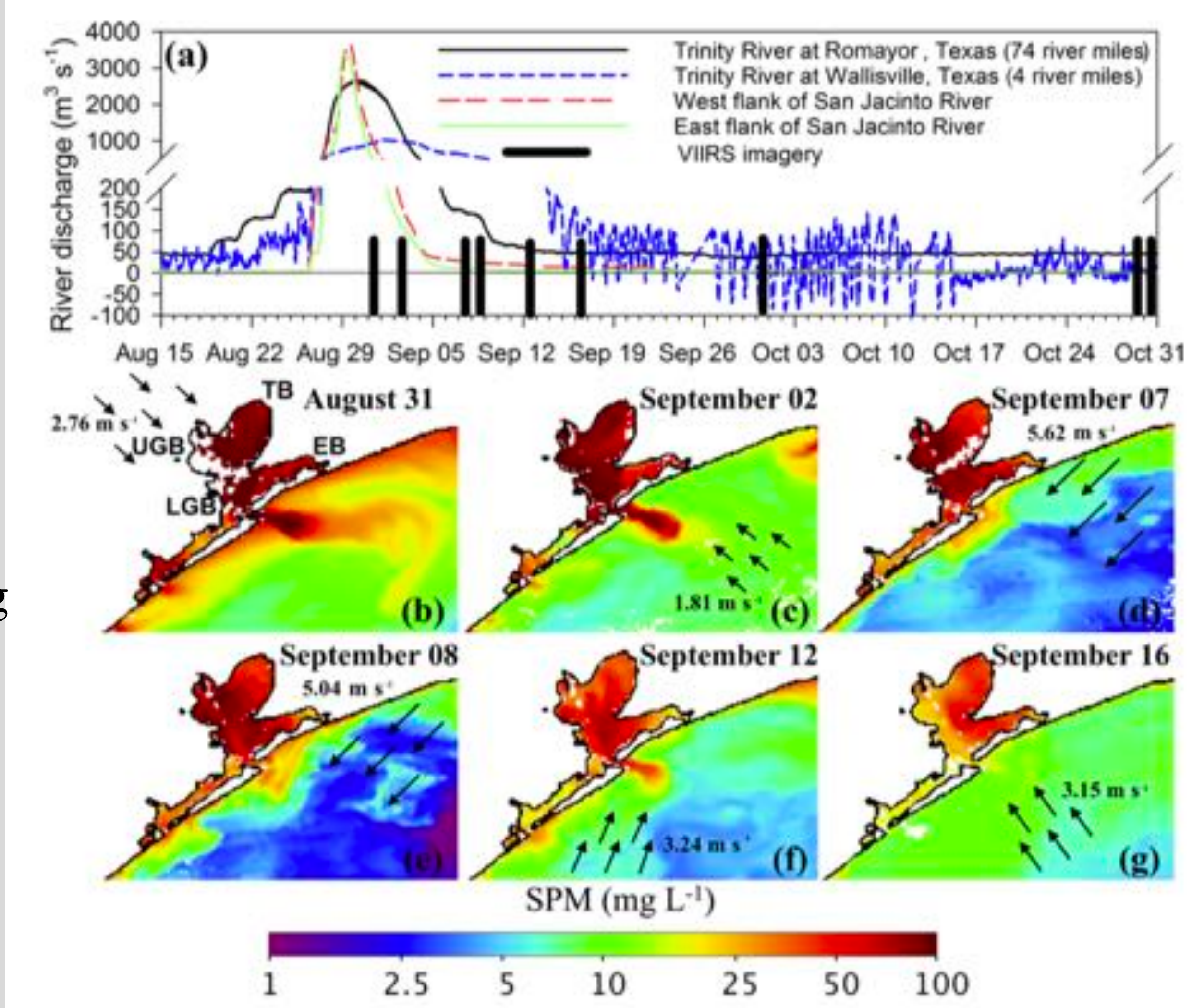


Optical property (backscattering coefficient) to SPM



SPM MAPS

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

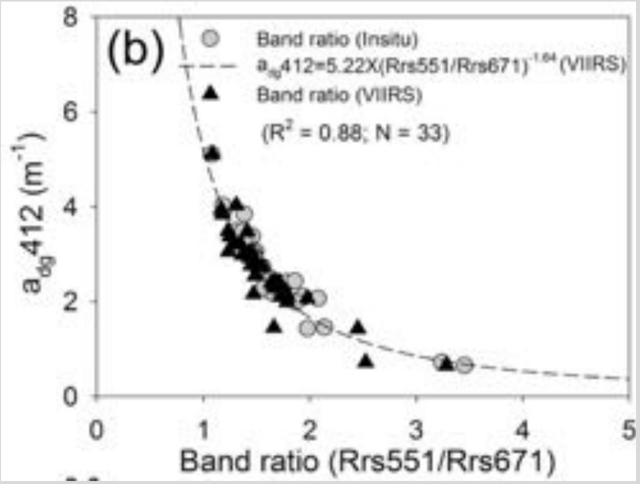


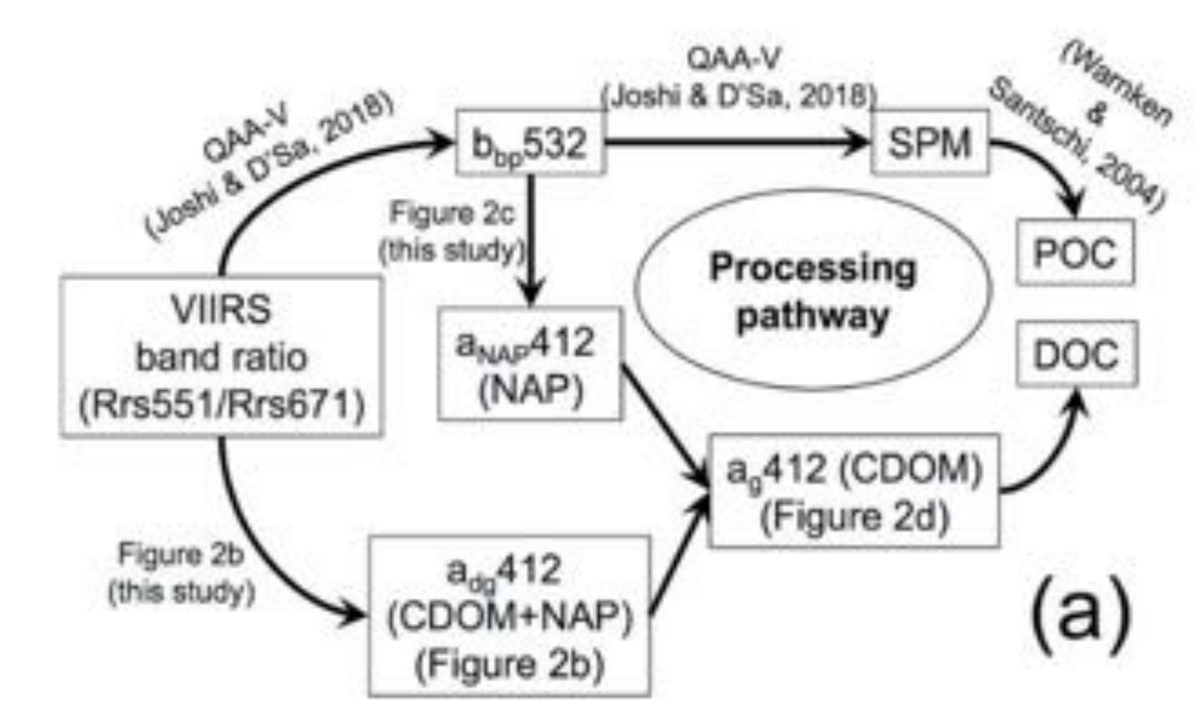
SPM dynamics following Hurricane Harvey

Joshi & D'Sa 2018-Biogeosciences

Coastal ocean optical-geochemical response to Hurricane Harvey

From: D'Sa, Joshi and Liu 2018-GRL





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

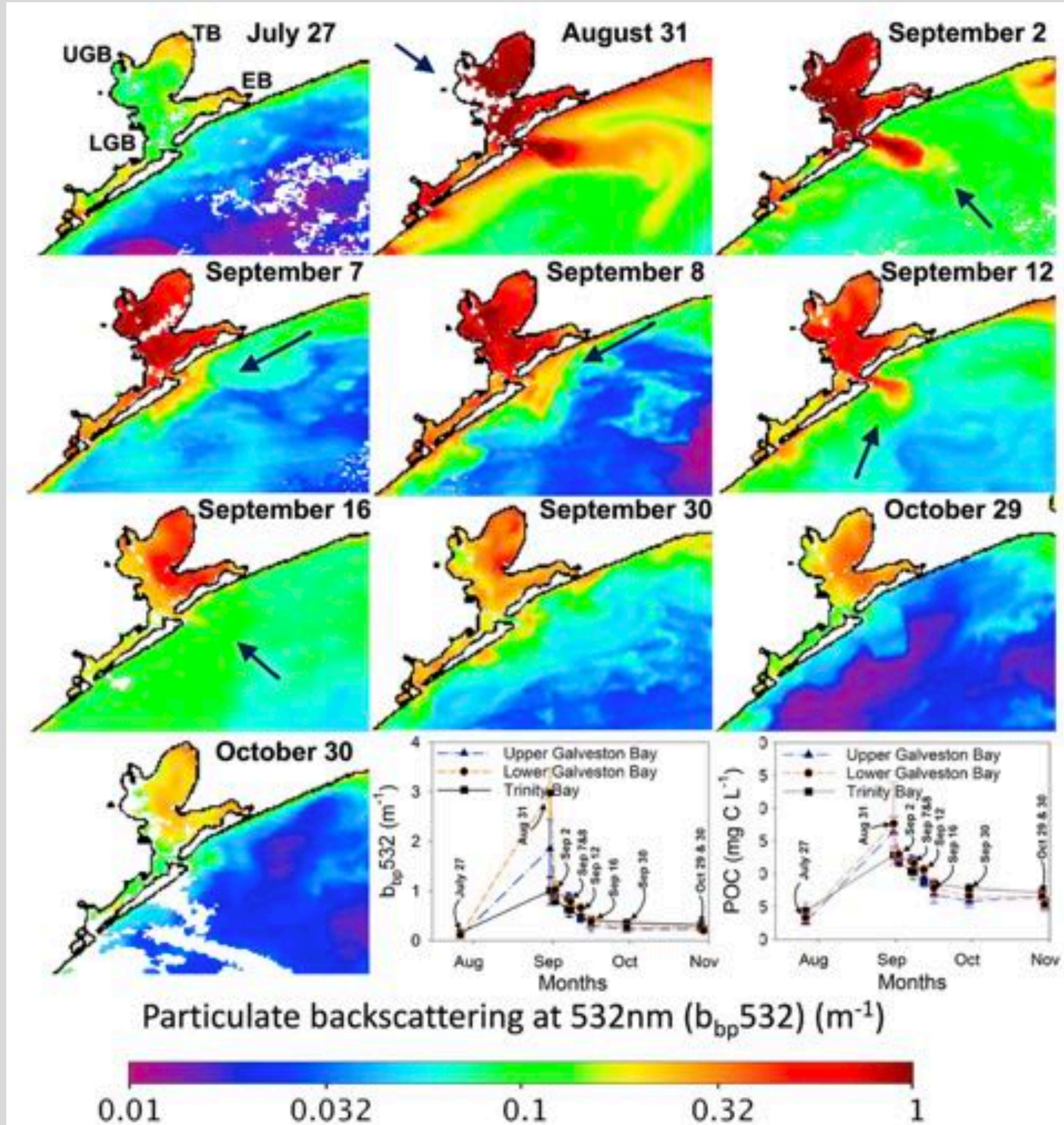
POC dynamics following Hurricane Harvey in Galveston Bay

$$SPM = 103.07 \times b_{bp}532 + 0.24$$

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

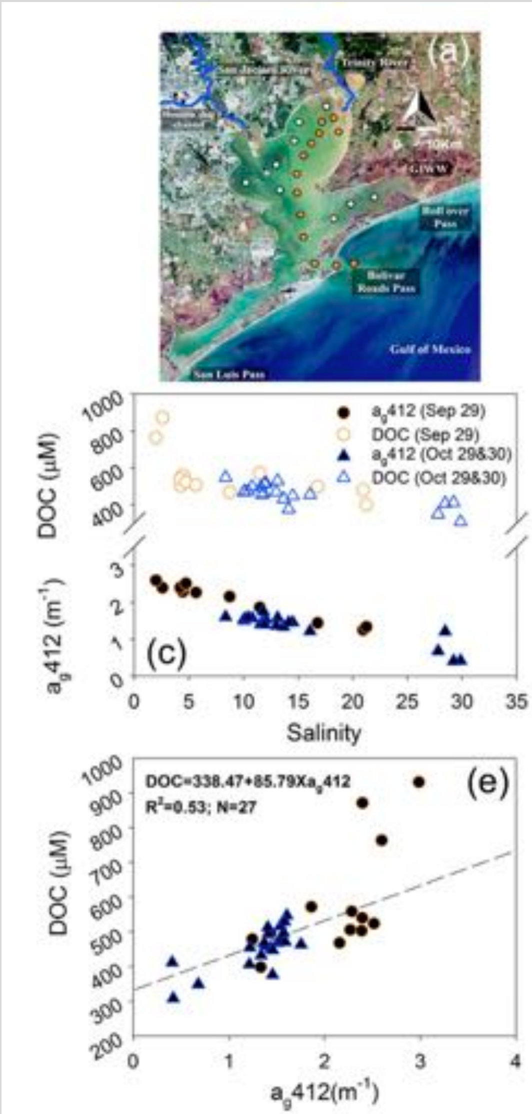
where POC* = POC/SPM.

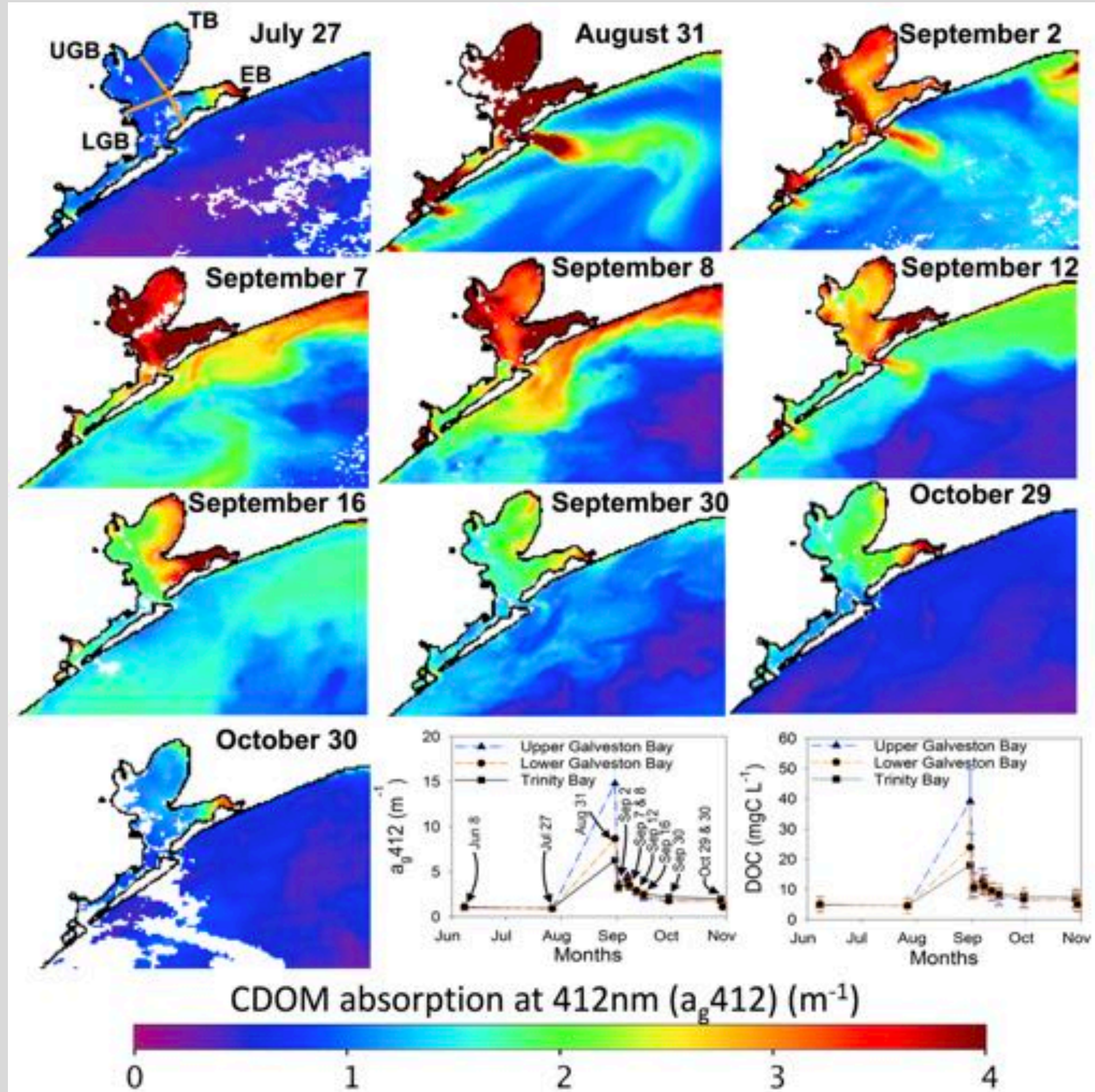
Warnken & Santschi 2004-
Sci. Total Environ.



D'Sa, Joshi and Liu 2018-GRL

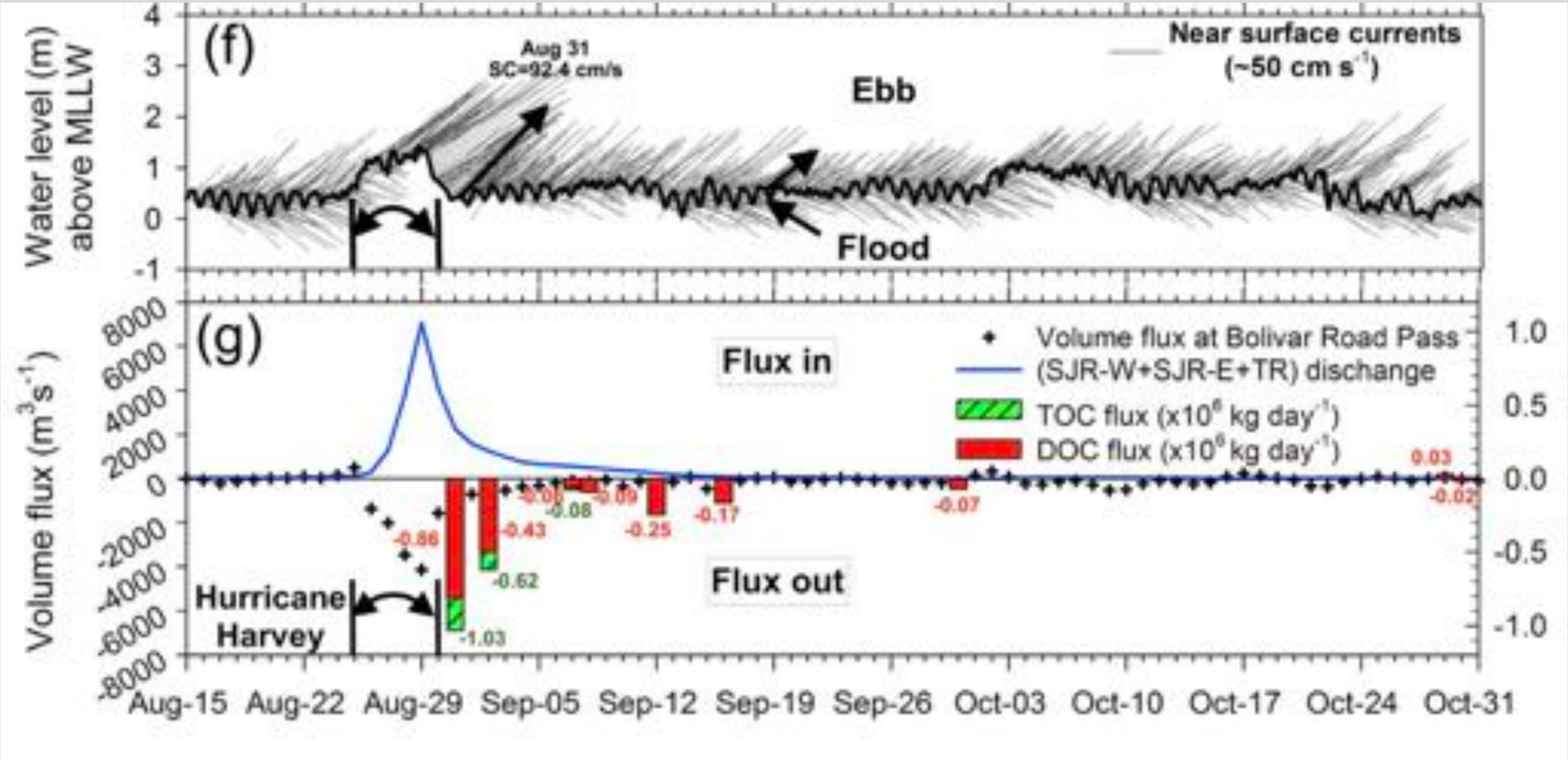
CDOM/DOC dynamics following Hurricane Harvey





Volume, DOC, POC fluxes linked to Hurricane Harvey

D'Sa, Joshi and Liu 2018-GRL



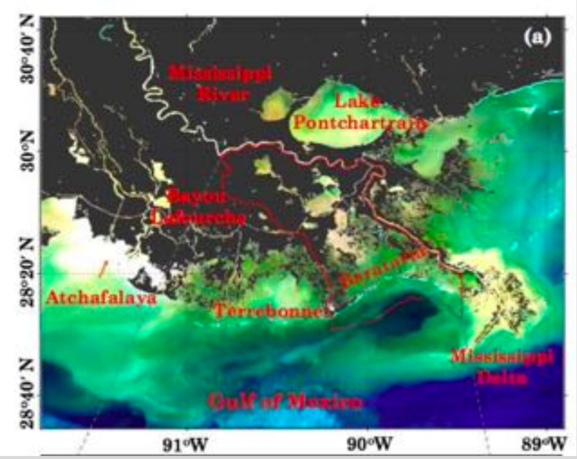
- Top: water level and surface currents at Galveston Bay entrance
- Bottom: TR+SJR discharge; +volume flux at entrance; DOC & POC fluxes

- 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

$$L_T(\lambda) = L_{ATM}(\lambda) + L_{SURF}(\lambda) + t_v L_w(\lambda)$$

$$Rrs = L_w(\lambda)/E_d(\lambda)$$



•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)

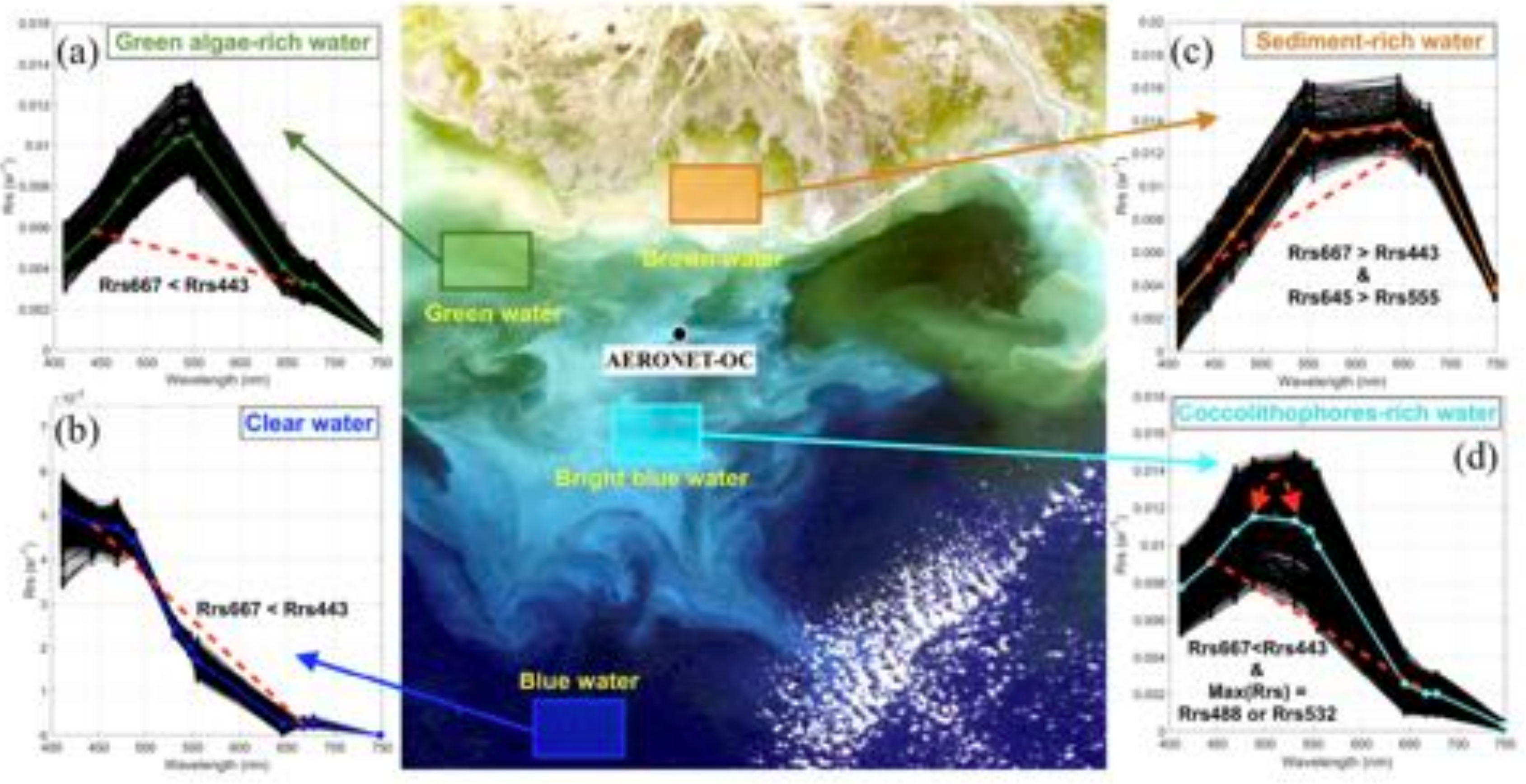


Fig. 4. Different water types in a MODIS-Aqua scene (December 13, 2012) collected over the nGoM. (a) Rrs spectra over the green water. (b) Rrs spectra over the blue water. (c) Rrs spectra over the brown water. (d) Rrs spectra corresponding to the bright blue waters likely due to coccolithophores. Colored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

From: Joshi & D'Sa 2020-IEEE TGRS

Adaptive atmospheric correction algorithms (AD-ATCOR; MODIS-Aqua)

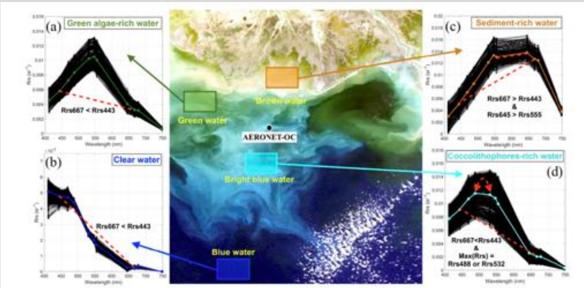
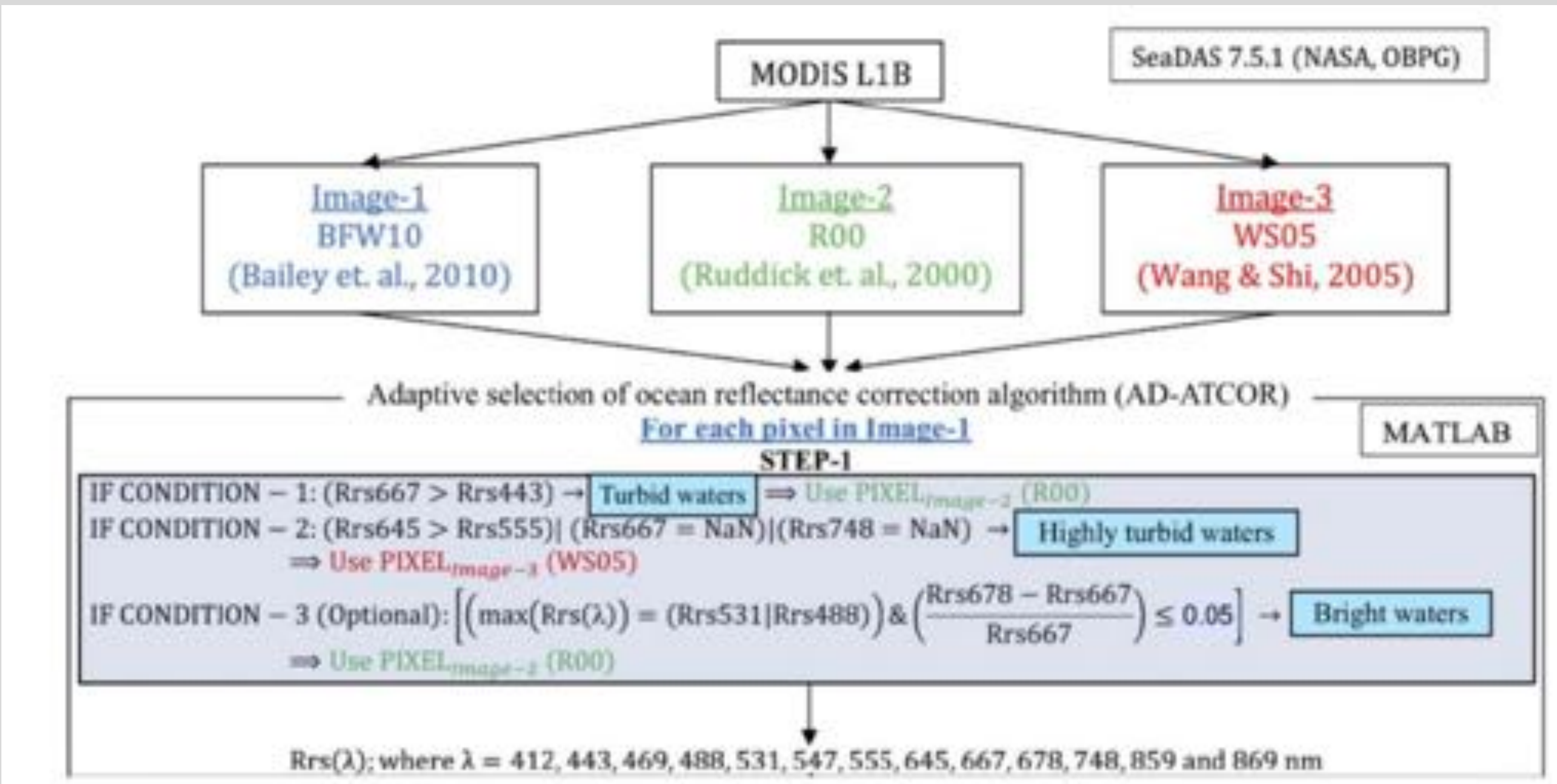


Fig. 4. Different water types in a MODIS-Aqua scene (December 13, 2012) collected over the nGoM. (a) Rrs spectra over the green water. (b) Rrs spectra over the blue water. (c) Rrs spectra over the brown water. (d) Rrs spectra corresponding to the bright blue waters likely due to coccolithophores. Colored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

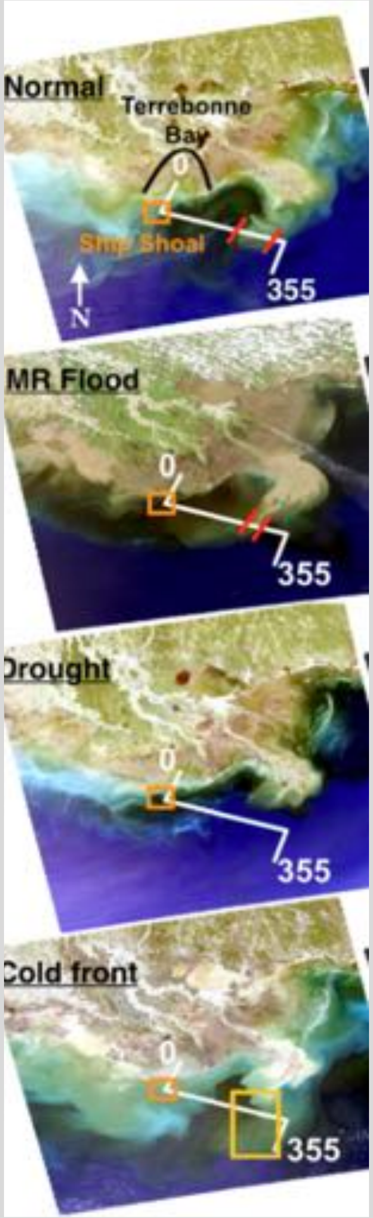
From: Joshi & D'Sa 2020-IEEE TGRS

- 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



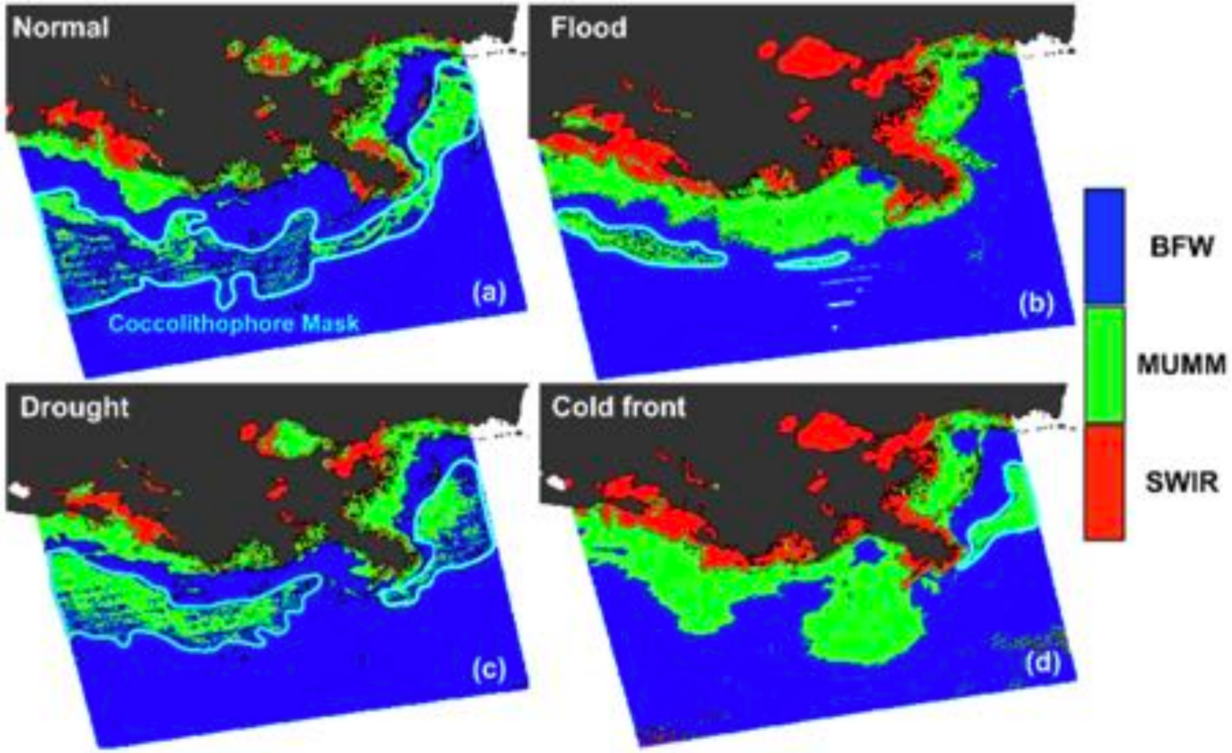


Fig. 7. Maps showing pixel-by-pixel application of three correction algorithms, BFW10 (blue), R00 (green), and WS05 (red), in heterogeneous waters of nGoM during (a) normal condition (May 6, 2017), (b) MR flood (April 13, 2008), (c) MR drought (October 19, 2012), and (d) passage of a cold front (February 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

$Rrs(\lambda)$; where λ = 412, 443, 469, 488, 531, 547, 555, 645, 667, 678, 748, 859 and 869 nm

Adaptive selection of Quasi-Analytical Algorithm (AD-QAA)

MATLAB

STEP-2:

$$rrs(\lambda) = \frac{Rrs(\lambda)}{0.52 + 1.7 \times Rrs(\lambda)}$$

STEP-3:

$$\rho_v = \log10\left(\frac{rrs555}{rrs667}\right) \text{ (QAA-V; Joshi \& D'Sa, 2018)}$$

$$\rho_{v5} = \log10\left(\frac{rrs443 + rrs488}{rrs555 + 5 \times rrs670 \times \left(\frac{rrs670}{rrs490}\right)}\right) \text{ (QAA-v5; Lee et al., 2002)}$$

STEP-4:

$$u(\lambda) = \frac{-g_0 + \left[g_0^2 + 4 \times g_1 \times rrs(\lambda)\right]^{0.5}}{2 \times g_1}$$

$g_0 = 0.0788$ & $g_1 = 0.2379$ if $\rho_v < 0.25$ (Joshi & D'Sa, 2018)

$g_0 = 0.0895$ & $g_1 = 0.1247$ if $\rho_v \geq 0.25$ (Lee et. al., 2002)

STEP-5: IF,

$\rho_v < 0.25$:

$$a_{tnw}555 = 10^{(0.091 - 1.800 \times \rho + 0.560 \times \rho^2)} \text{ (QAA-V)}$$

$\rho_v \geq 0.25$ & $\rho_v < 0.65$:

$$a_{tnw}555 = 10^{(0.275 - 2.674 \times \rho + 0.813 \times \rho^2)} \text{ (QAA-V)}$$

$\rho_v \geq 0.65$ & $\rho_v < 0.75$:

$$a_{tnw}555 = \frac{\left[10^{(0.275 - 2.674 \times \rho_v + 0.813 \times \rho_v^2)} + 10^{(-1.146 - 1.366 \times (\rho_{v5}) - 0.469 \times (\rho_{v5})^2)}\right]}{2} \text{ (QAA-V \& QAA-v5)}$$

$\rho_v \geq 0.75$:

$$a_{tnw}555 = 10^{(-1.146 - 1.366 \times \rho_{v5} - 0.469 \times \rho_{v5}^2)} \text{(QAA-v5)}$$

STEP-6:

$$bb_{tnw}555 = \frac{(a_{tnw}555 + a_w555) \times u555}{(1 - u555)} - bb_w555$$

STEP-7:

$$\eta_v = -0.566 - 1.395 \times \log10\,(bb_{tnw}555) \text{ if } \rho_v < 0.25 \text{ (D'Sa et. al., 2007)}$$

$$\eta_{v5} = 2 \times \left(1 - 1.2 \times e^{\left(-0.9 \times \frac{rrs443}{rrs555}\right)}\right) \text{ if } \rho_v \geq 0.25 \text{ (Lee et. al., 2002)}$$

STEP-8:

$$bb_t(\lambda) = bb_w(\lambda) + bb_{tnw}555 \times \left(\frac{555}{\lambda}\right)^{\eta}$$

STEP-9:

$$a_t(\lambda) = bb_t(\lambda) \times \left(\frac{1 - u(\lambda)}{u(\lambda)}\right)$$

Adaptive QAA (AD-QAA: QAA-V & QAA-v5)

From: Joshi & D'Sa 2020 IEEE TGRS

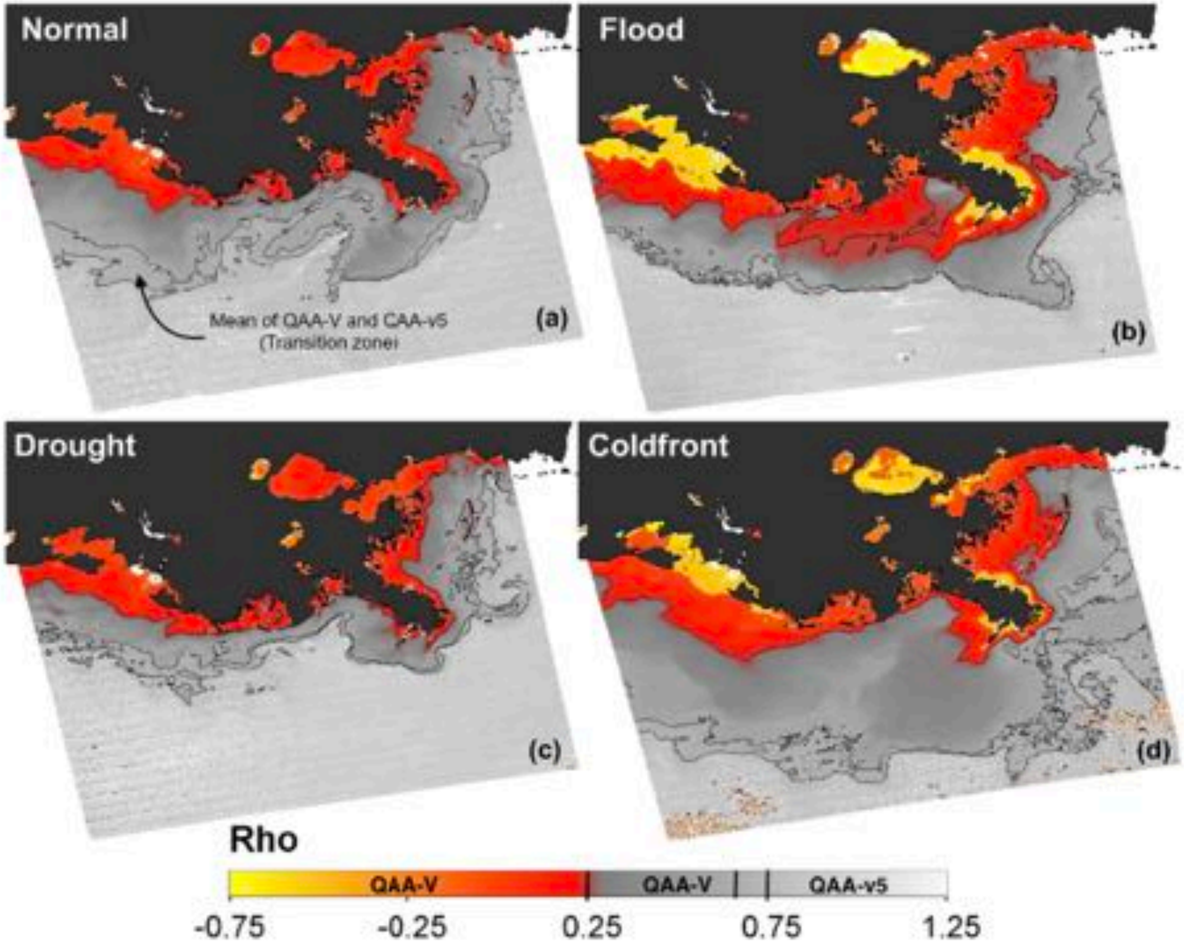
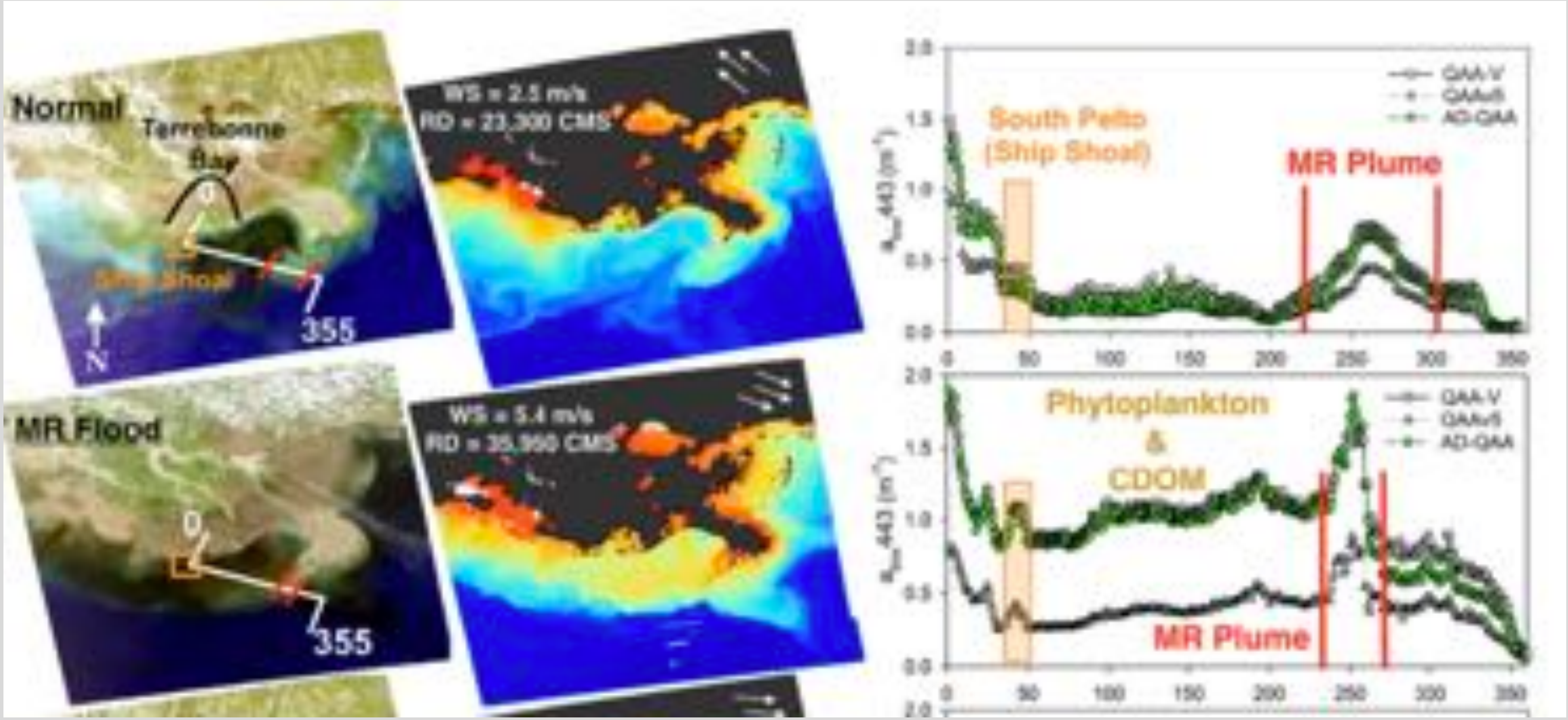


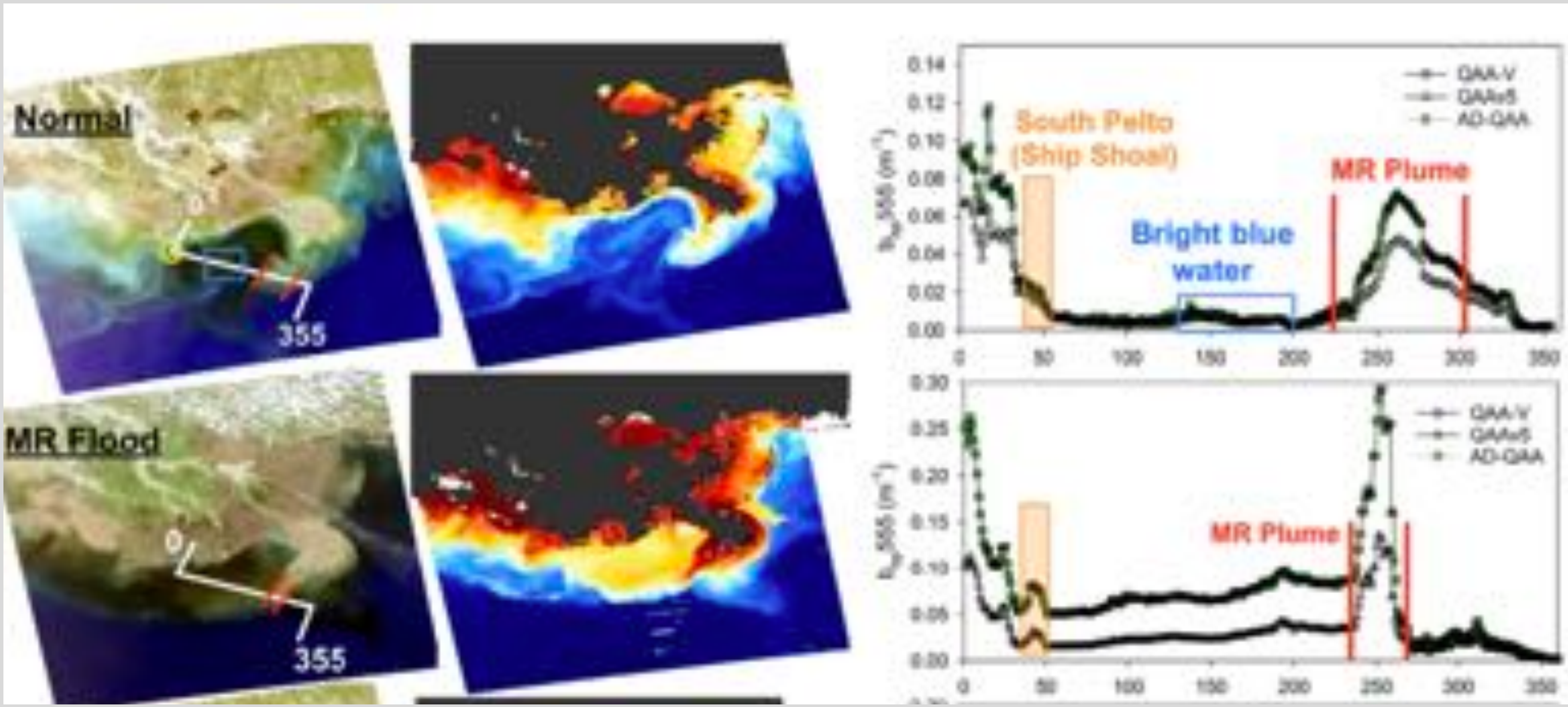
Fig. 9. MODIS-Aqua Rho (ρ) maps showing pixel-by-pixel application (AD-QAA) of two QAAs algorithms, QAA-V and QAA-v5, using ρ thresholds (step-5 in Fig. 2) in heterogeneous waters of nGoM during four conditions. (a) Normal condition (May 6, 2017). (b) MR flood (April 13, 2008). (c) MR drought (October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

AD-QAA: total absorption coefficients

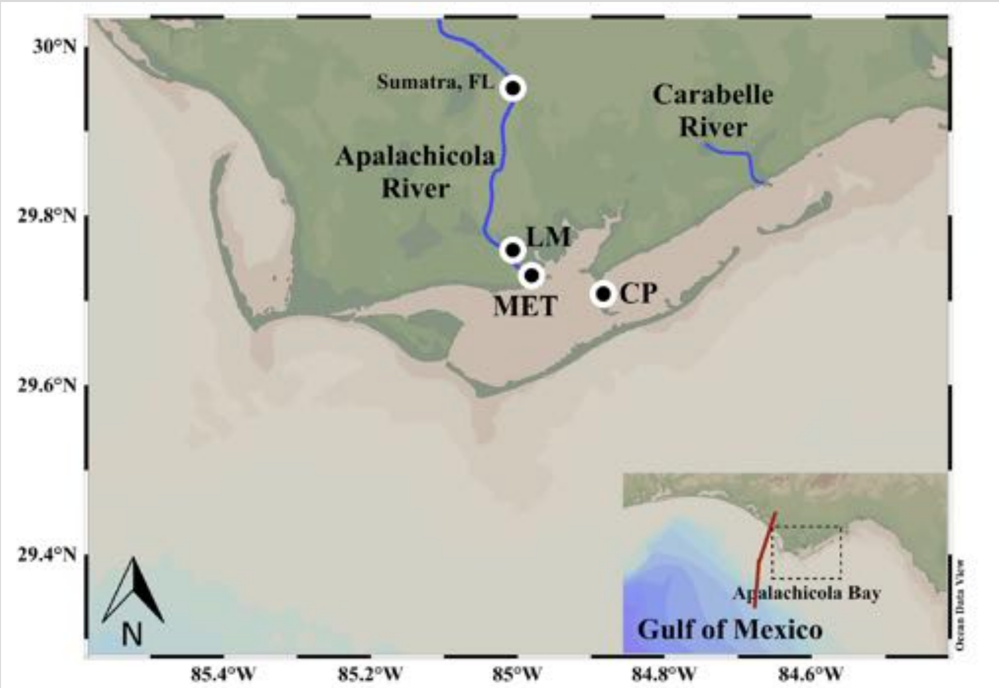
Joshi & D'Sa 2020-IEEE TGRS

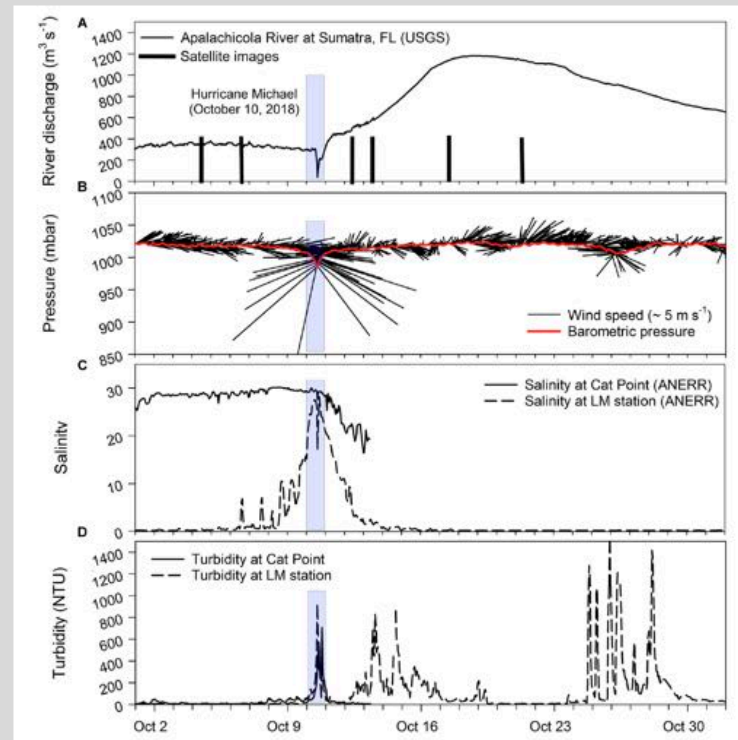


AD-QAA: backscattering coefficients

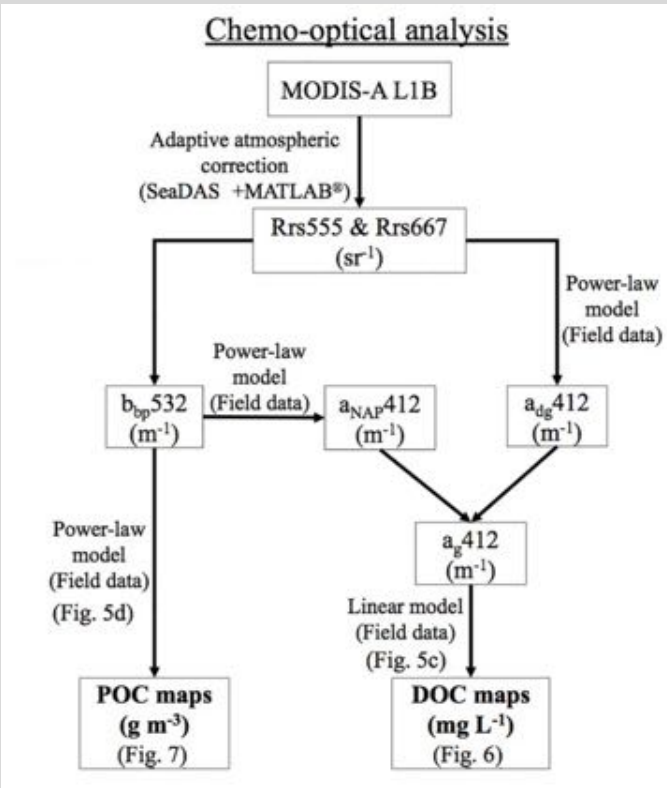


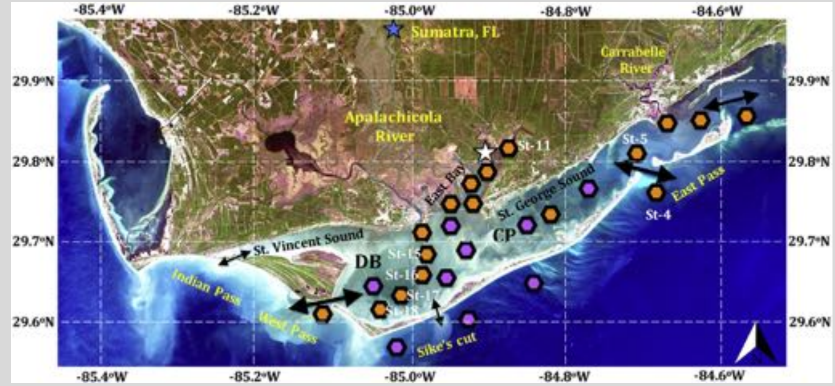
Application: Hurricane Michael impact (Oct 10, 2018) using MODIS Aqua

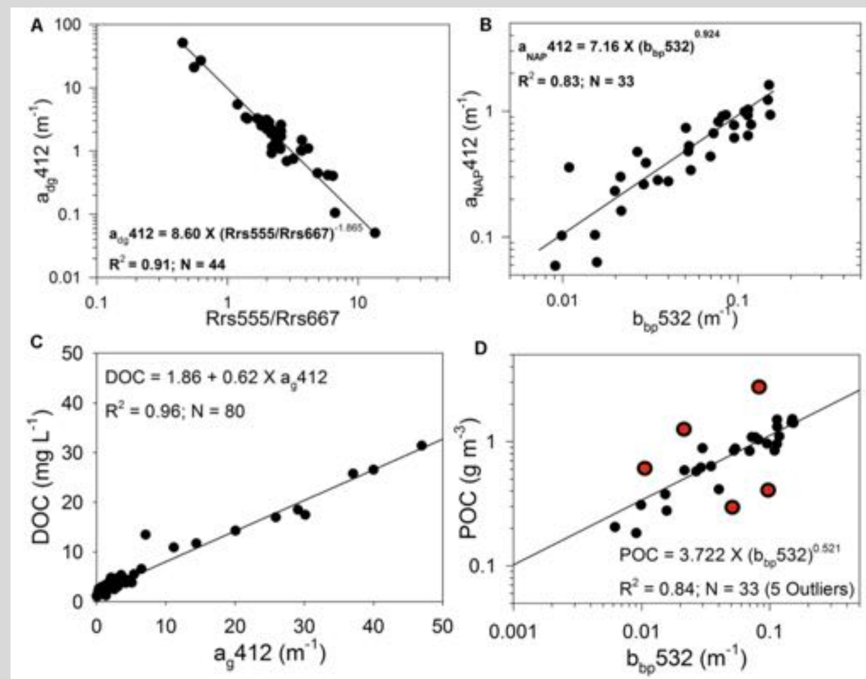




POC and DOC maps in Apalachicola Bay



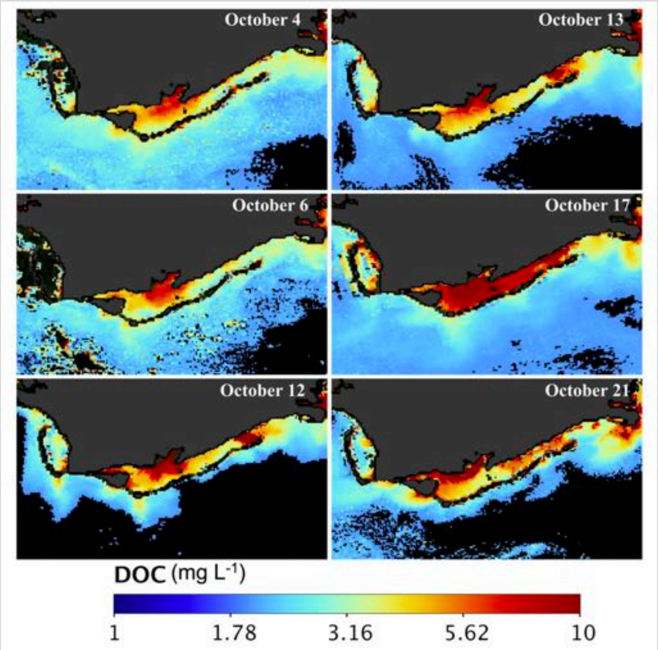


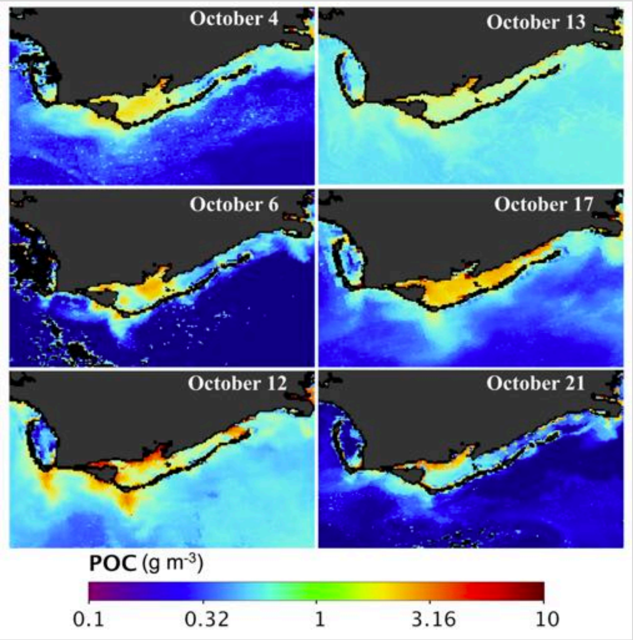


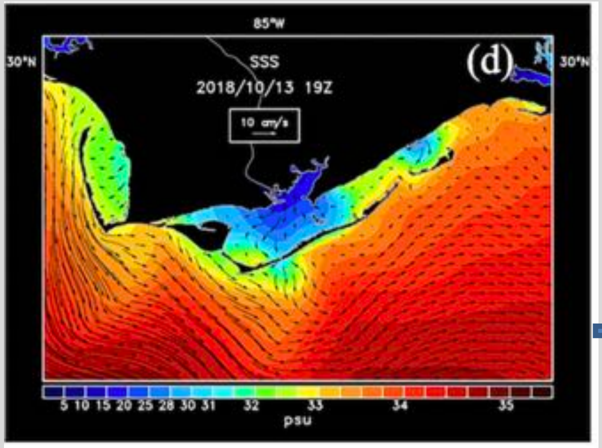
D'Sa et al. 2019-Frontiers Marine Science

Hurricane Michael: DOC and POC distribution and fluxes

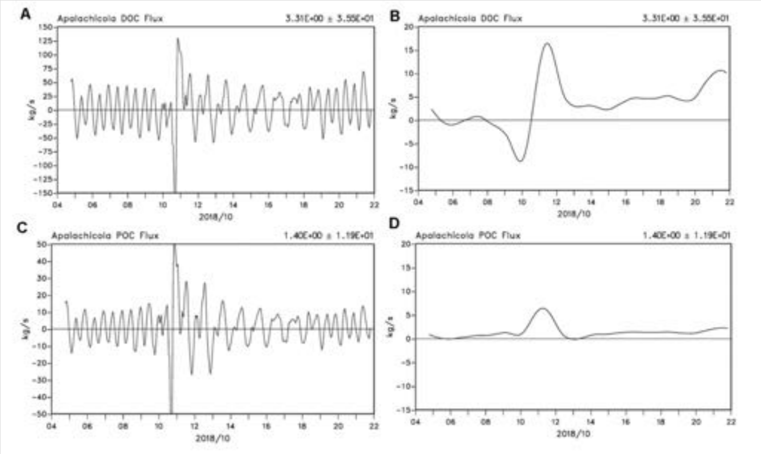
D'Sa et al. 2019-FMS







NCOM hydrodynamic model



Fluxes of DOC and POC

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

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