Shallow Water Bathymetry With Multi-spectral Satellite Ocean Color Sensors:

Leveraging Temporal Variation

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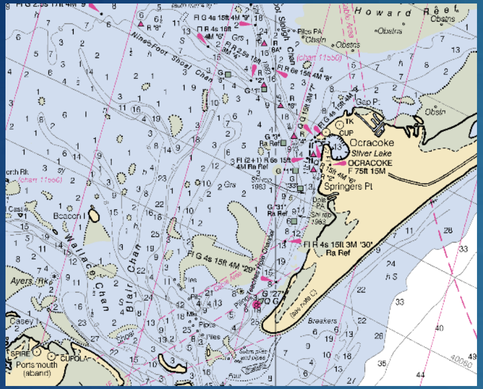
NOCCG Seminar
Nov 4, 2020
3:00 pm – 4:00 pm

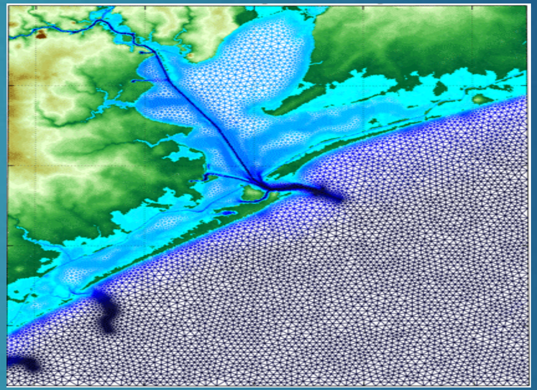
A key element for navigation and ocean science

- Navigation



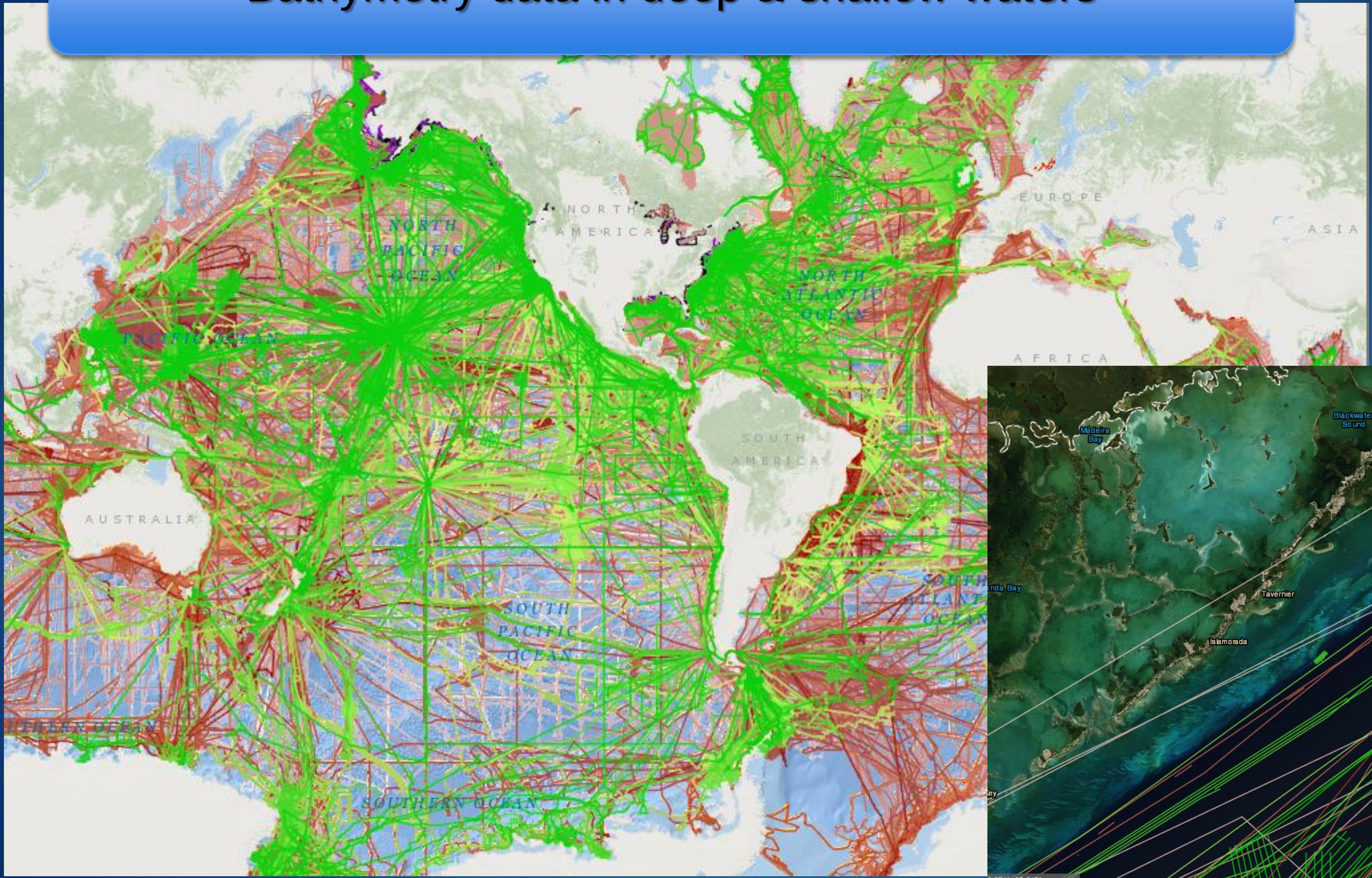
- Coastal morphology

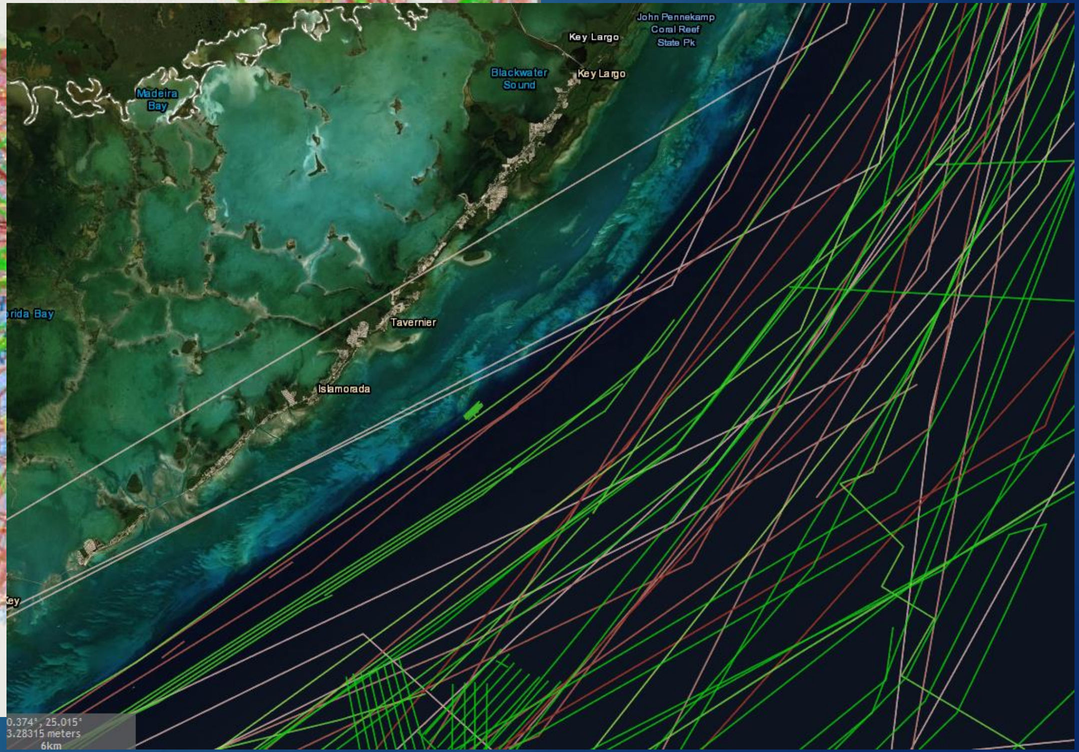
- Dynamic modeling



- Marine biology

Bathymetry data in deep & shallow waters





Source:
NOAA National Centers for Environmental Information

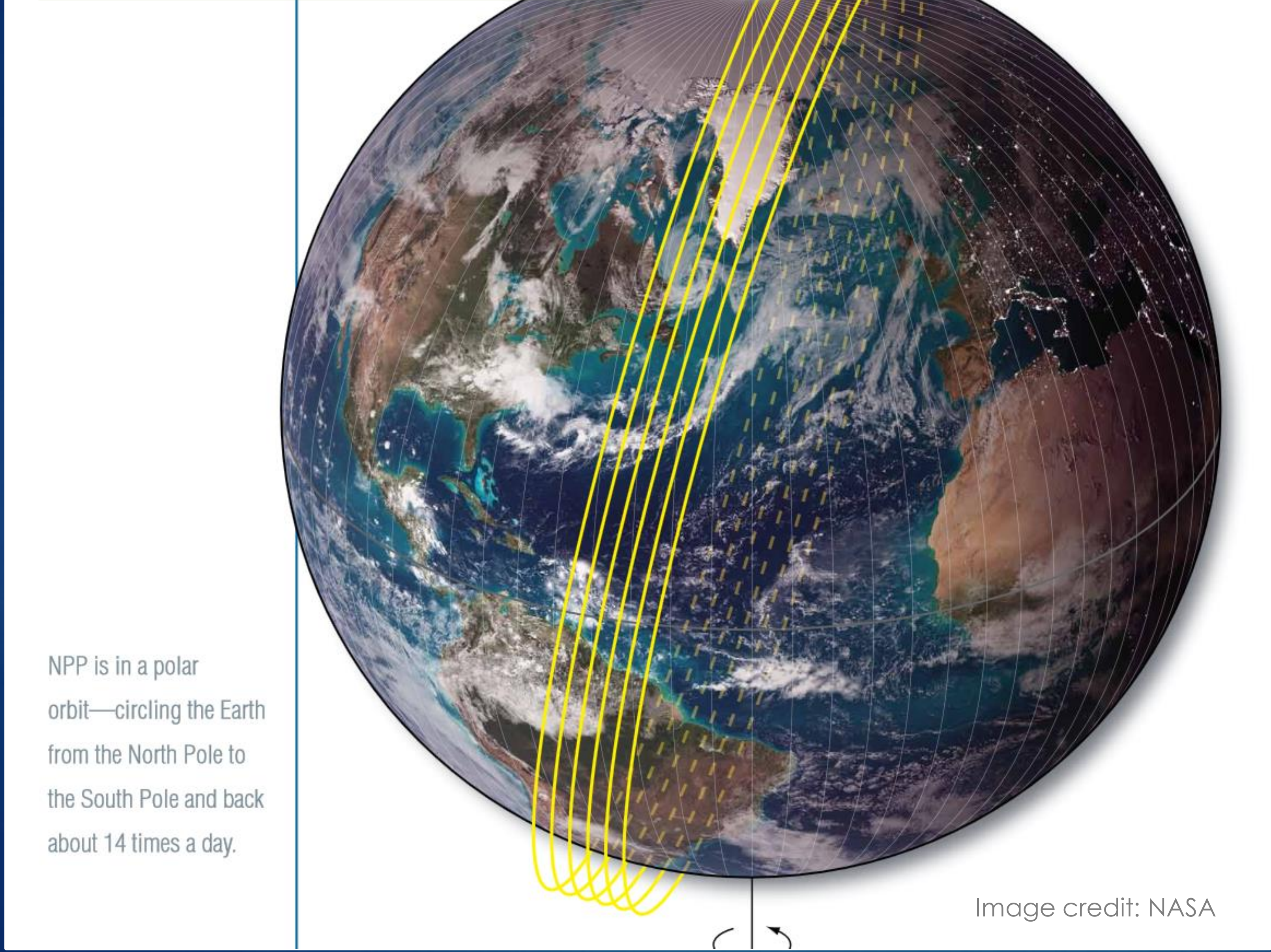
Optical sensing of shallow waters

- Passive approach (e.g., Ocean Color) and active approach (e.g., LiDAR)
- Ocean color remote sensing provides an effective means of mapping shallow water bathymetry on synoptic scales

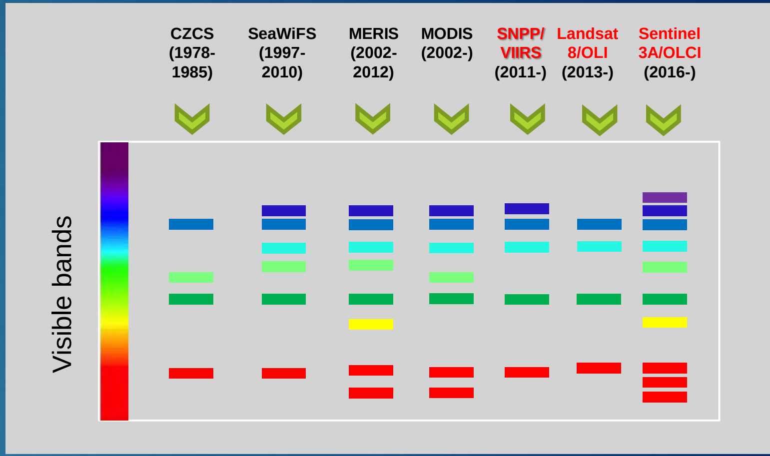
An “ocean color” snapshot

A conceptualized bathymetry map

Mapping the Blue Marble from polar-orbiting ocean color satellites

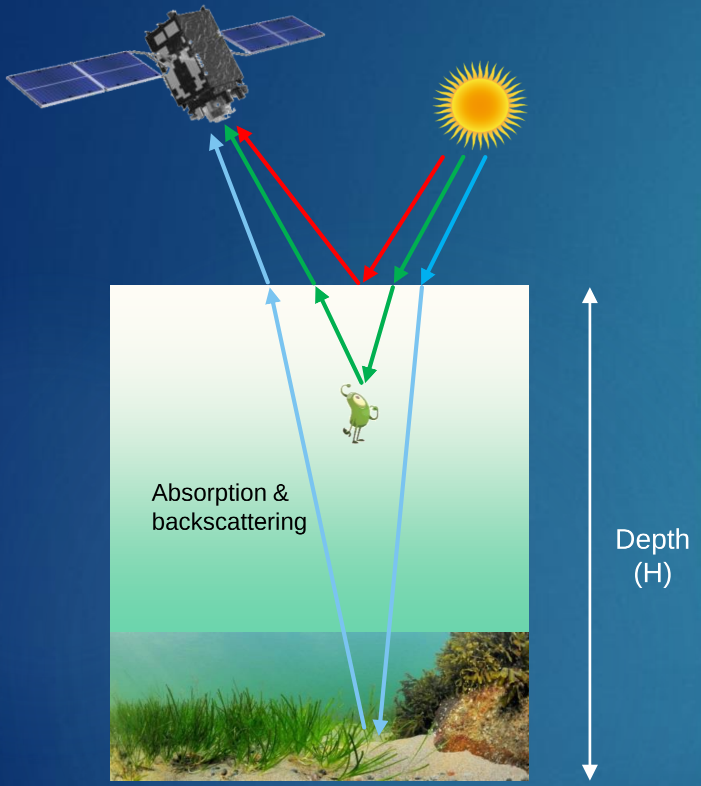


- Multi-spectral ocean color images



- Frequent revisit
  - SNPP VIIRS: everyday
  - Sentinel 3A OLCI: 2-3 days
  - Landsat 8 OLI: 16 days
- Moderate-high spatial resolutions
  - SNPP VIIRS: 750 m
  - Sentinel 3A OLCI: 300 m
  - Landsat 8 OLI: 30 m

Remote sensing reflectance in shallow waters



Bottom albedo (B)

- Remote sensing reflectance

Remote sensing reflectance (Rrs) varies with water depth (H), bottom albedo (B), and water inherent optical properties (IOPs) including light absorption and backscattering coefficients.

Forward model (it is nonlinear)

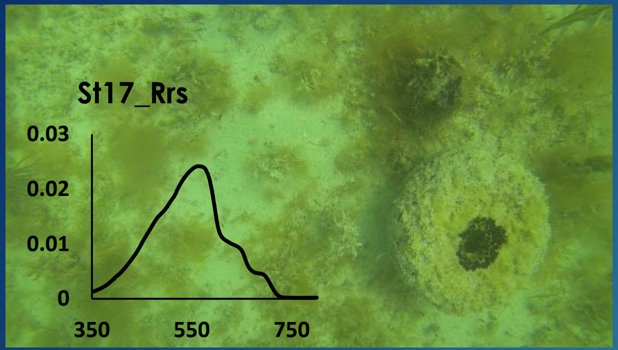
$$r_{rs}(\lambda) \approx r_{rs}^{dp}(\lambda)\cdot\left\{1-\exp\left[-\left(\frac{1}{\cos\theta_w}+\frac{D_0\left(1+D_1\cdot u(\lambda)\right)^{0.5}}{\cos\theta_a}\right)\cdot k(\lambda)\cdot H\right]\right\}+\frac{B(\lambda)}{\pi}\exp\left[-\left(\frac{1}{\cos\theta_w}+\frac{D_0'\left(1+D_1'\cdot u(\lambda)\right)^{0.5}}{\cos\theta_a}\right)\cdot k(\lambda)\cdot H\right]$$

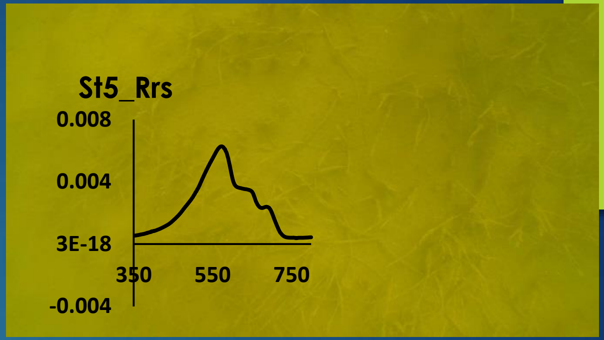
Lee et al. (1999)

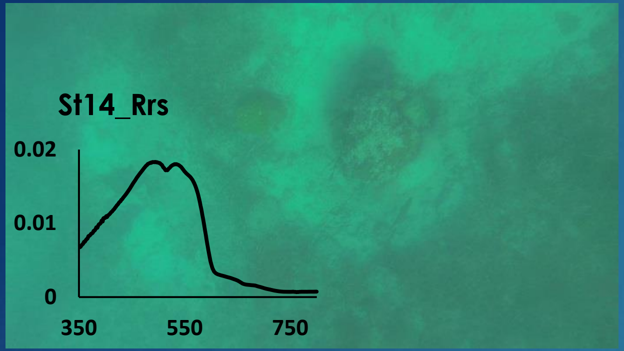
- Optically shallow waters

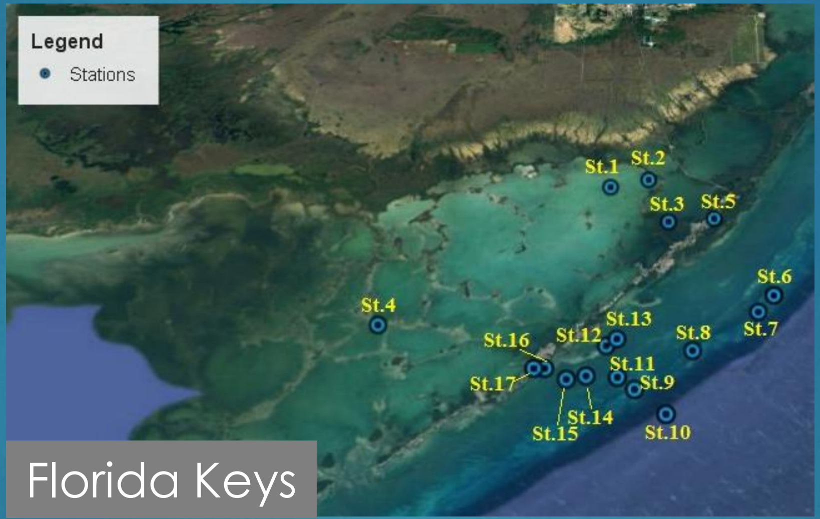
Optically shallow waters are those where the light reflected off the seafloor still contributes significantly to the water-leaving radiance

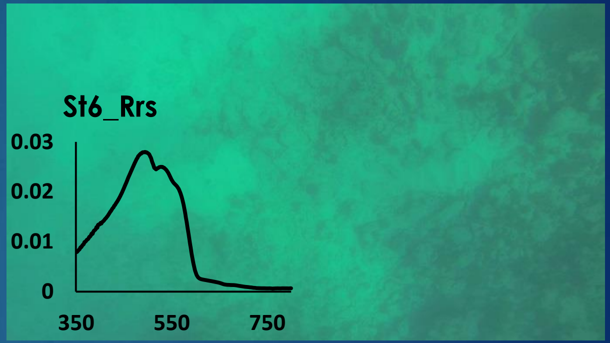
Rrs spectra over seagrass and algae bottoms

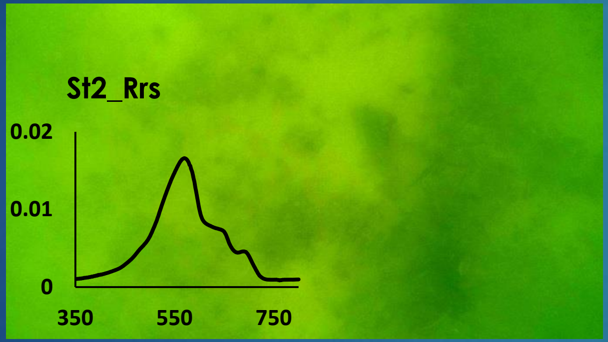


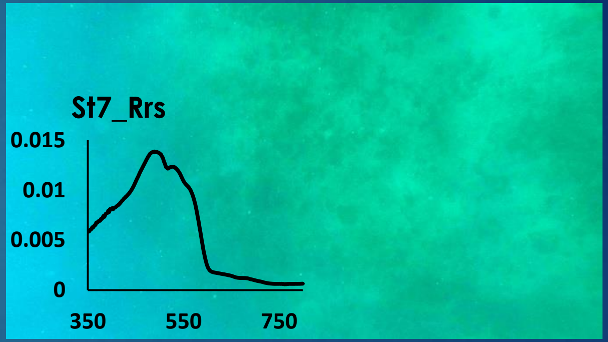


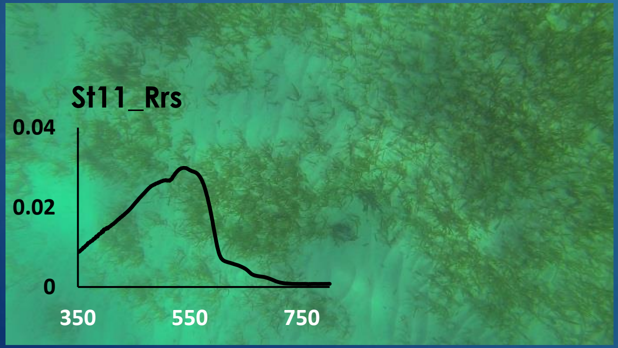


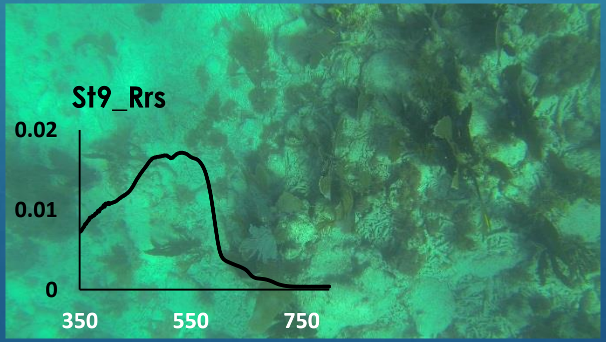


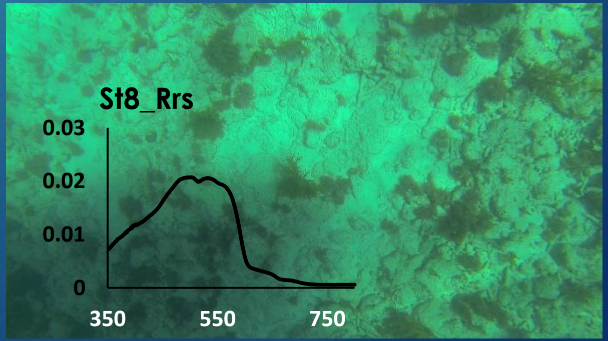












Wei and Lee (2020), unpublished

Rrs spectra over coral reefs

Wei and Lee (2020), unpublished

Inversion of ocean color spectra

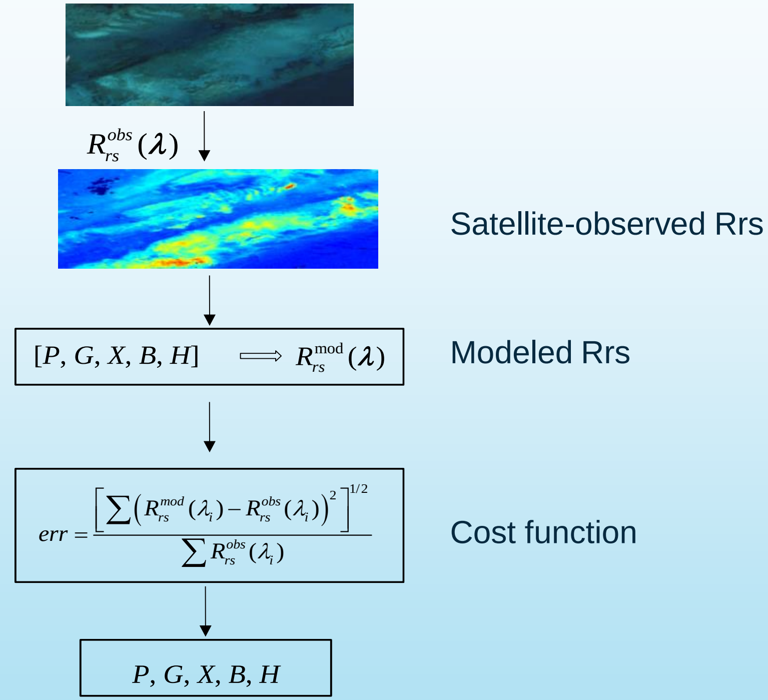
Analytical inversion of the ocean color spectra is not straightforward as there exist more unknowns than available numbers of equations/relationships

$$\begin{cases} R_{rs}(\lambda_1) = Fun\left[P(\lambda_1),\ G(\lambda_1),\ X(\lambda_1),\ B(\lambda_1),\ H\right] \\ R_{rs}(\lambda_2) = Fun\left[P(\lambda_2),\ G(\lambda_2),\ X(\lambda_2),\ B(\lambda_2),\ H\right] \\ \quad . \\ \quad . \\ R_{rs}(\lambda_n) = Fun\left[P(\lambda_n),\ G(\lambda_n),\ X(\lambda_n),\ B(\lambda_n),\ H\right] \end{cases}$$

P : Absorption coefficient of phytoplankton
G : Absorption coefficient of CDOM and detritus
X : Backscattering coefficient of particles
B : Bottom albedo
H : Water depth

At least five bands are required to derive five unknowns

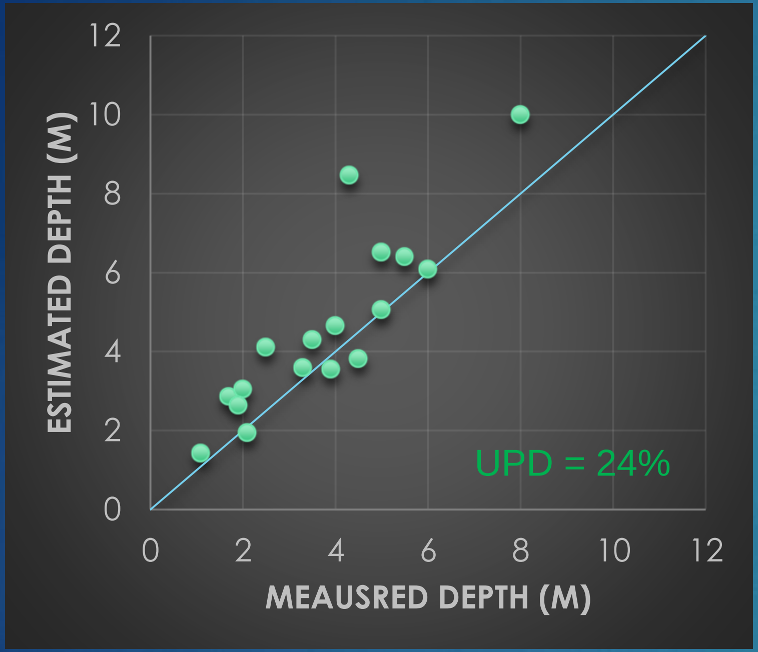
Spectral-optimization algorithm (SOA)



This approach does not require in situ measurements for calibration

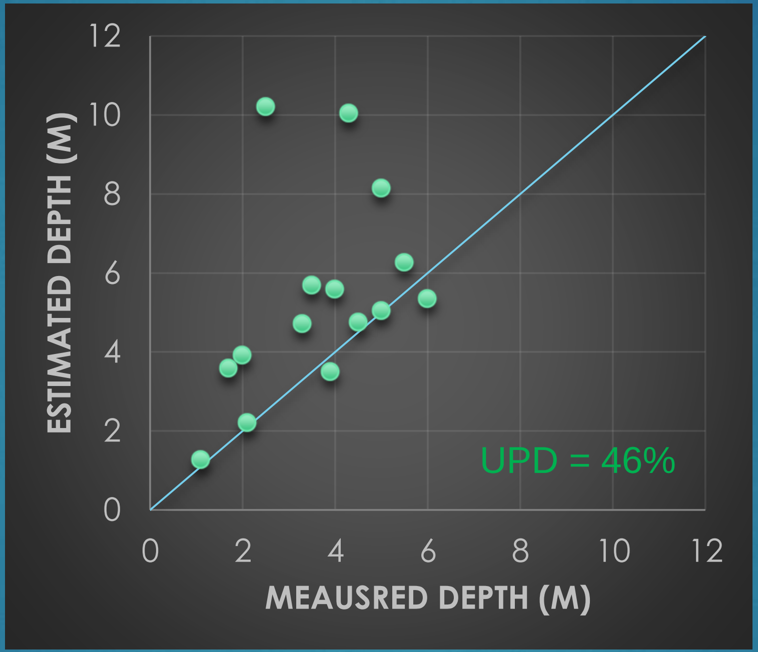
Dependence on band numbers

Hyperspectral



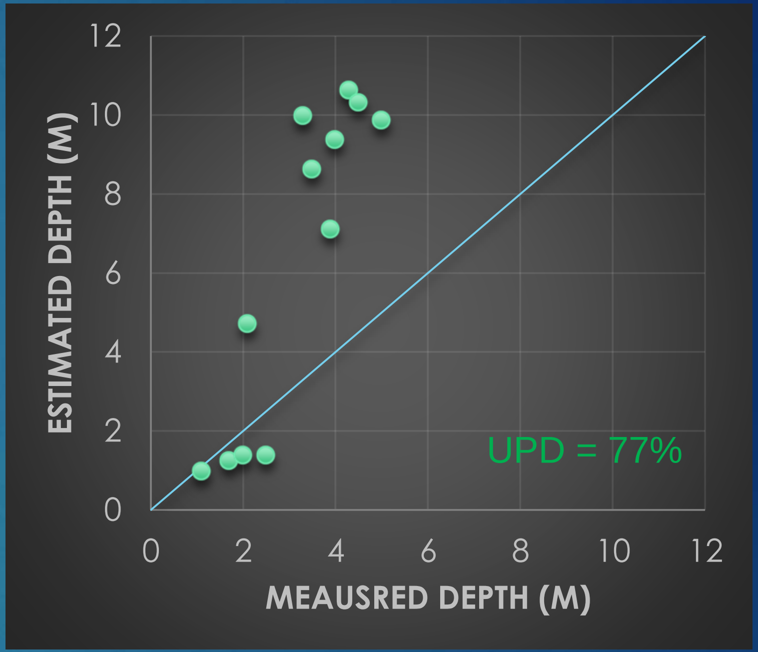
400-700 nm, every 5 nm

Five bands (SNPP/VIIRS)



412, 443, 486, 551, 671

Four bands (Landsat 8/OLLI)

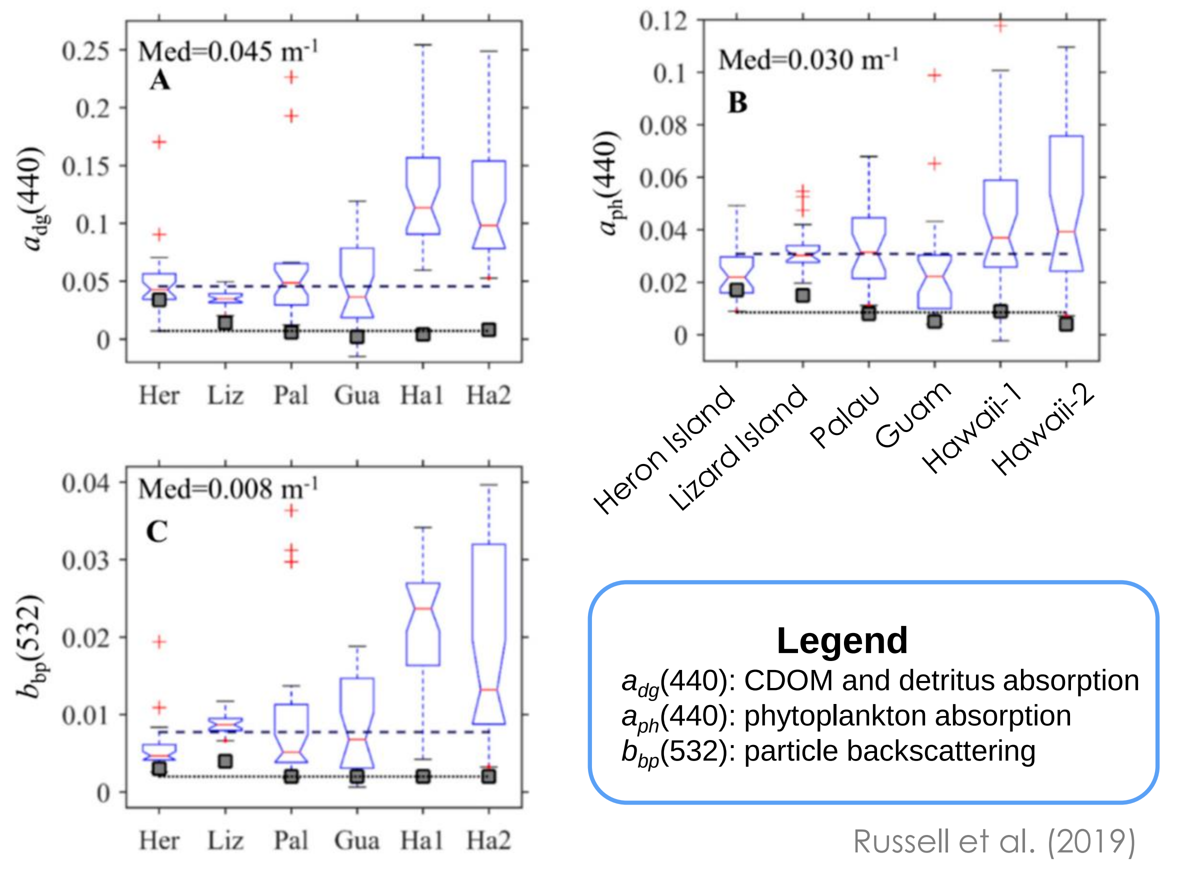


443, 482, 561, 655

- Hyper-spectral Rrs can be used for accurate retrieval of water depth from SOA
- It is more difficult to use multi-spectral Rrs for the retrieval of water depth with SOA

Variation of water absorption and backscattering

Spatial variation

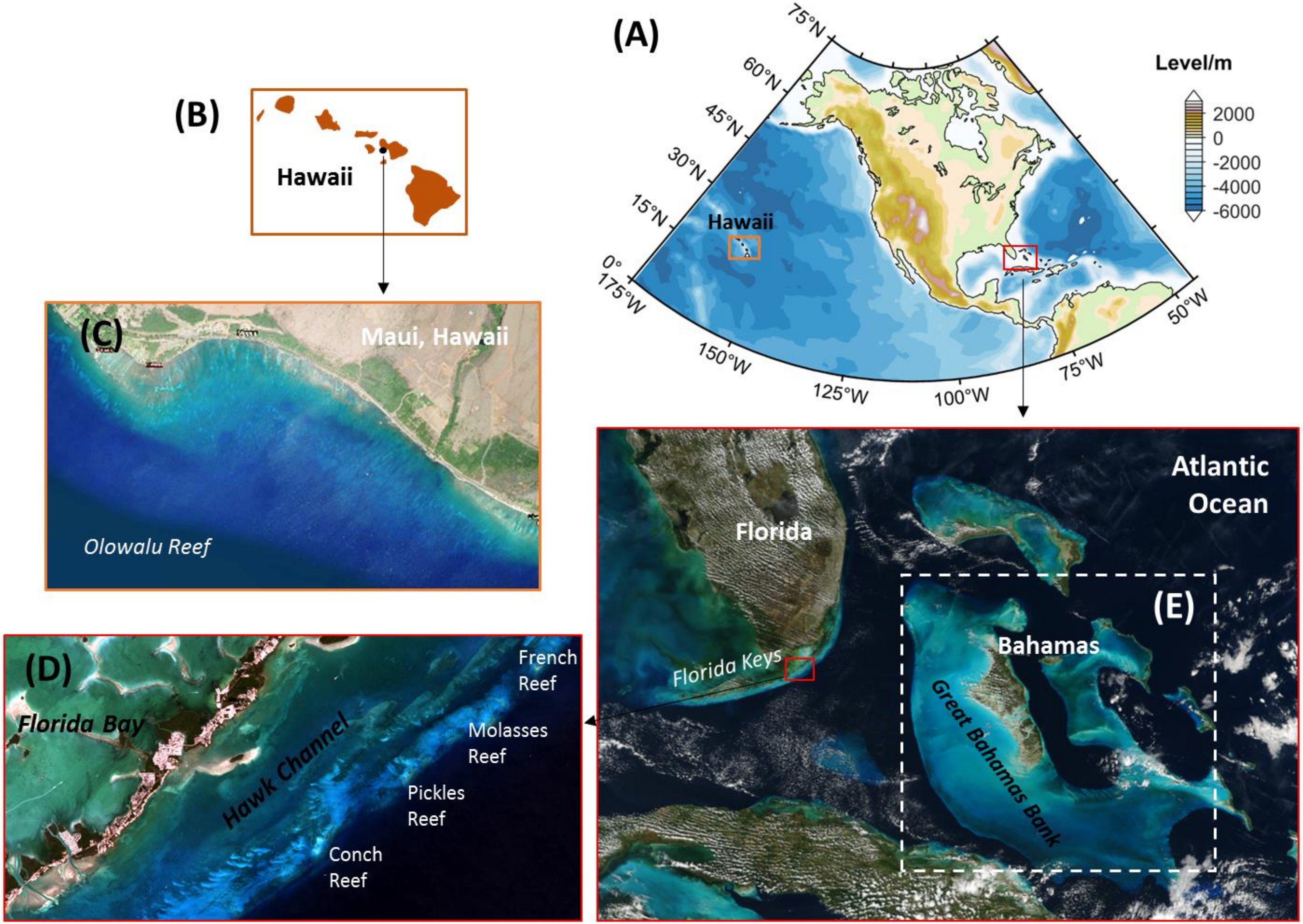


Legend

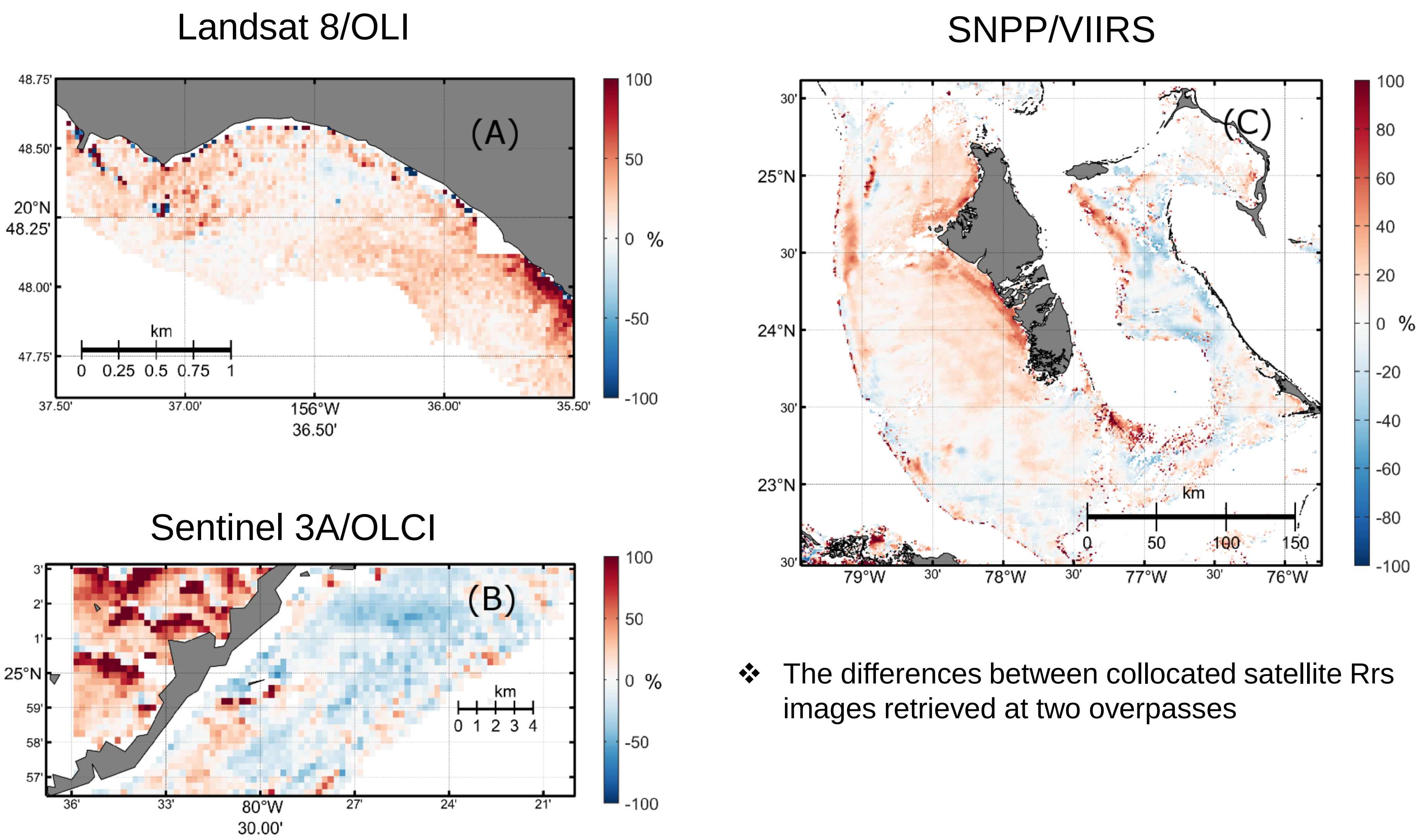
a_{dg}(440): CDOM and detritus absorption
a_{ph}(440): phytoplankton absorption
b_{bp}(532): particle backscattering

Russell et al. (2019)

Temporal variation


(A)
75°N
60°N
45°N
30°N
15°N
0°
175°W
150°W
125°W
100°W
75°W
50°W
Level/m
2000
0
-2000
-4000
-6000
Hawaii
(B)
Hawaii
(C)
Maui, Hawaii
Olowalu Reef
Atlantic Ocean
Florida
Florida Keys
(E)
Bahamas
Great Bahamas Bank
(D)
Florida Bay
Hawk Channel
French Reef
Molasses Reef
Pickles Reef
Conch Reef

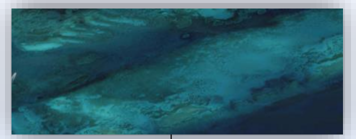
Temporal variation of satellite Rrs images (443 nm)



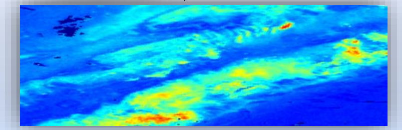
- The differences between collocated satellite Rrs images retrieved at two overpasses

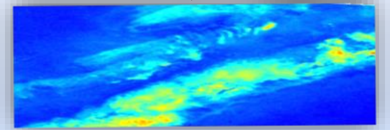
Leveraging the temporal variation

Two-spectrum optimization approach (2-SOA)



$R_{rs,1}^{obs}(\lambda)$ $R_{rs,2}^{obs}(\lambda)$





$[P_1, G_1, X_1, B, H] \Longrightarrow R_{rs,1}^{mod}(\lambda)$

$[P_2, G_2, X_2, B, H] \Longrightarrow R_{rs,2}^{mod}(\lambda)$

$$err = \frac{\left[\sum\left(R_{rs,1}^{mod}(\lambda_i) - R_{rs,1}^{obs}(\lambda_i)\right)^2 + \sum\left(R_{rs,2}^{mod}(\lambda_i) - R_{rs,2}^{obs}(\lambda_i)\right)^2\right]^{1/2}}{\sum R_{rs,1}^{obs}(\lambda_i) + \sum R_{rs,2}^{obs}(\lambda_i)}$$

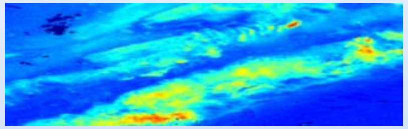
$P_1, G_1, X_1, P_2, G_2, X_2, B, H$

New

VS

One-spectrum optimization approach (1-SOA)

$R_{rs}^{obs}(\lambda)$



$[P, G, X, B, H] \Longrightarrow R_{rs}^{mod}(\lambda)$

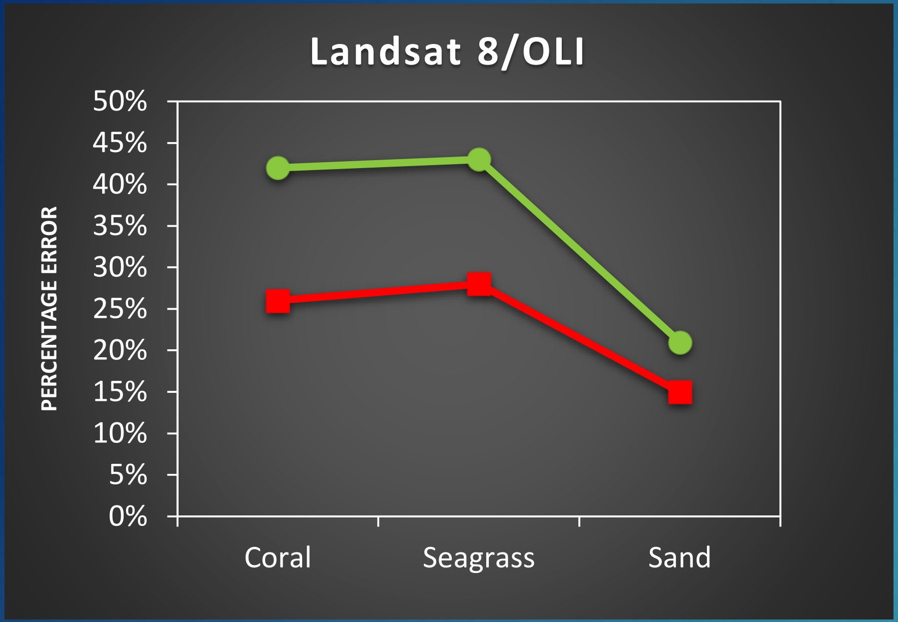
$$err = \frac{\left[\sum\left(R_{rs}^{mod}(\lambda_i) - R_{rs}^{obs}(\lambda_i)\right)^2\right]^{1/2}}{\sum R_{rs}^{obs}(\lambda_i)}$$

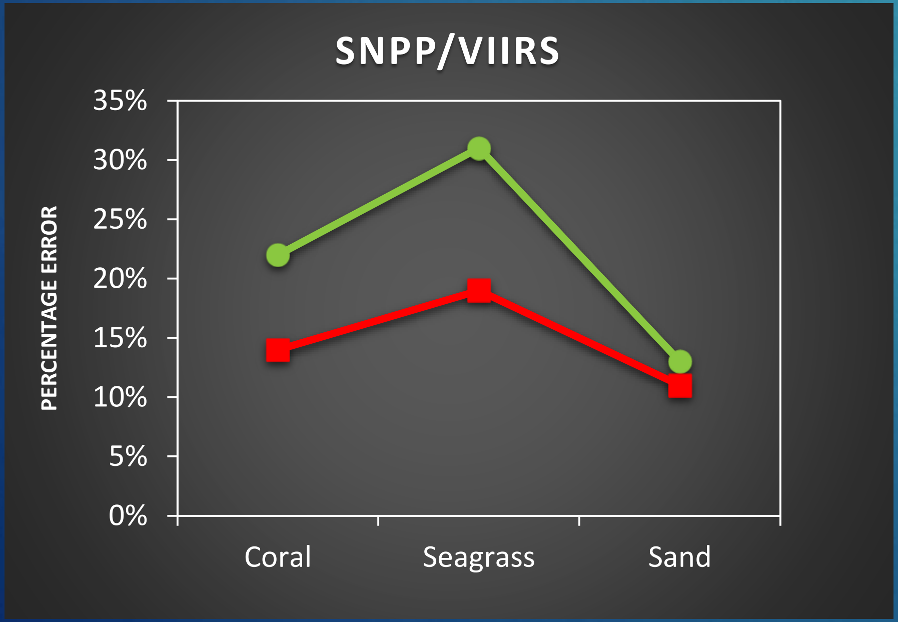
P, G, X, B, H

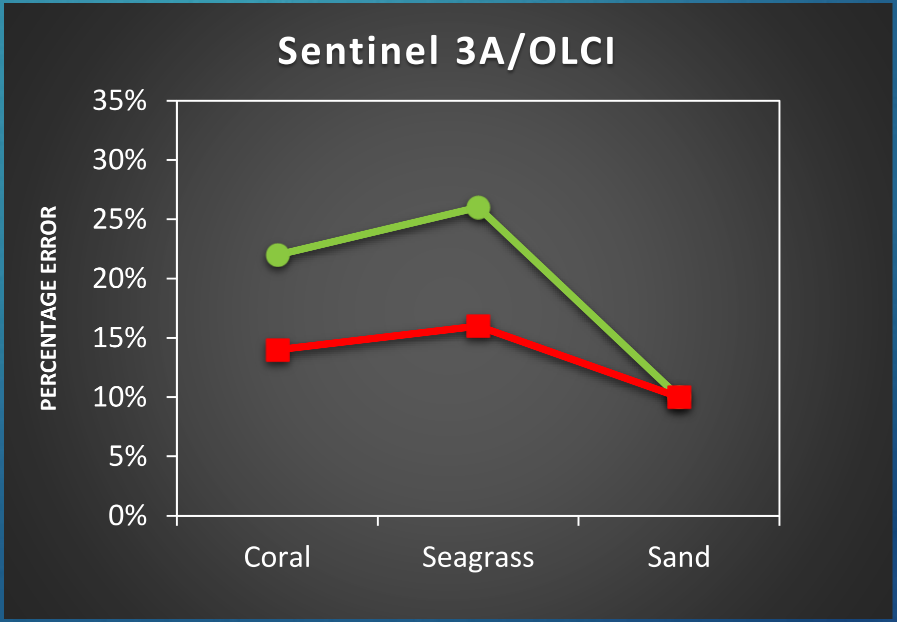
Evaluation with synthetic data

Shallow-water radiative transfer simulations:

- A range of water depths: 0.5 – 30 m
- Three types of benthic substrates: corals, seagrass, sand
- A wide range of light absorption & backscattering coefficients
- Paired Rrs spectra are constructed for each depths & benthic substrates

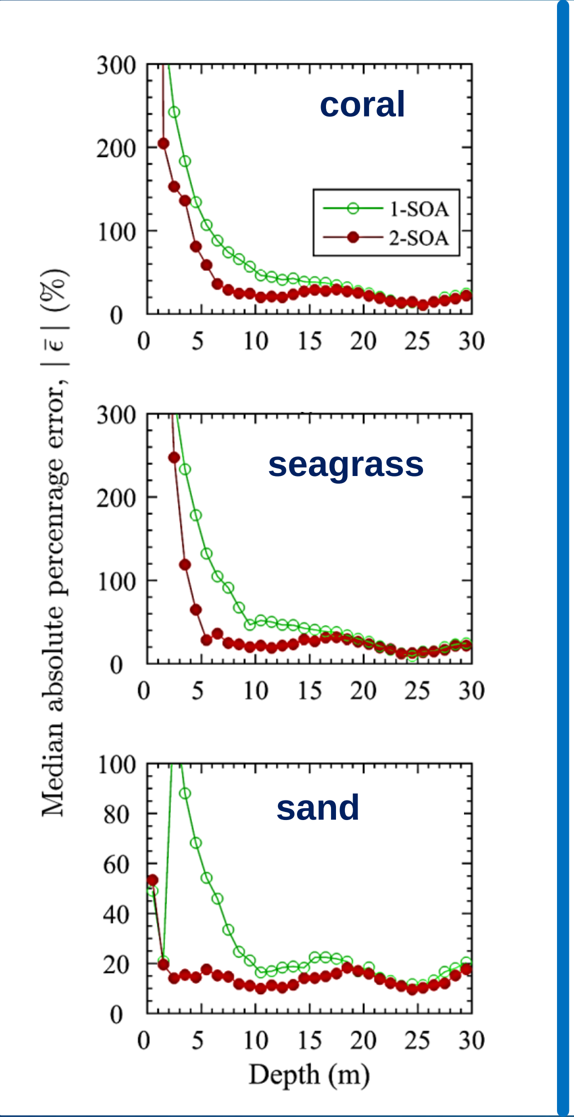


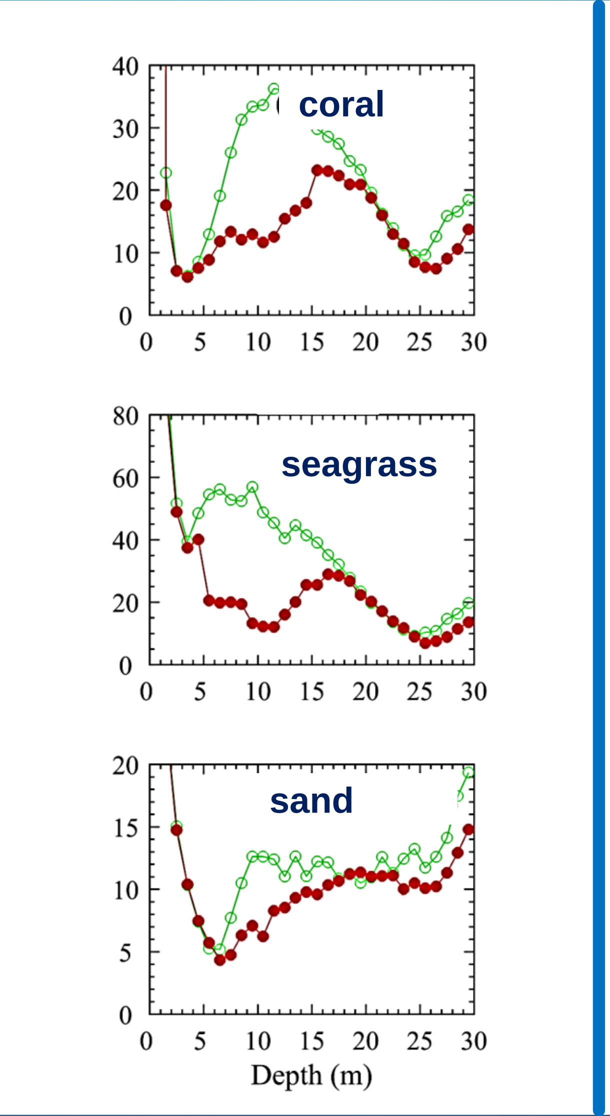


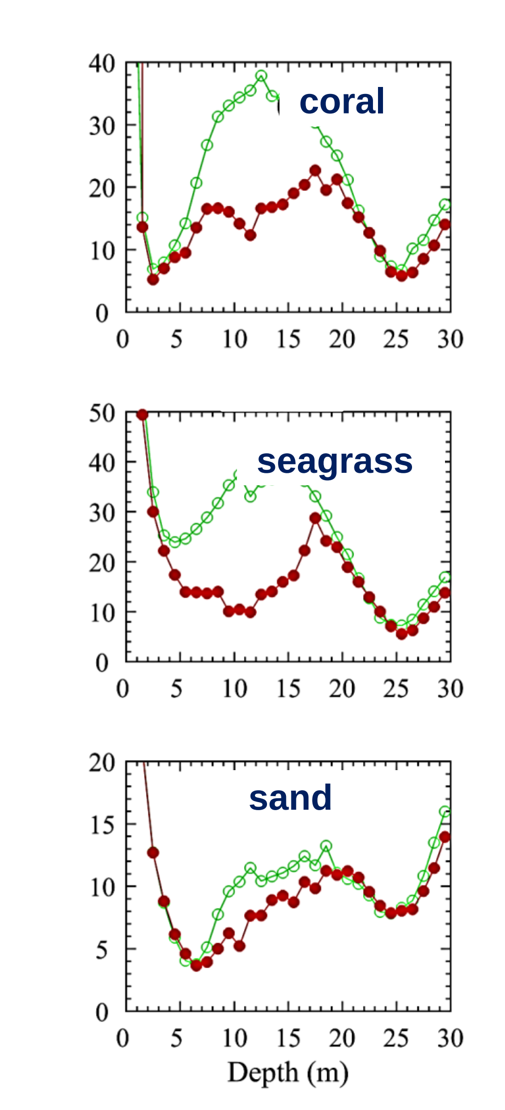


Comparisons of the model performance for depth retrieval

- Landsat 8/OLI
- SNPP/VIIRS
- Sentinel 3A/OLCI



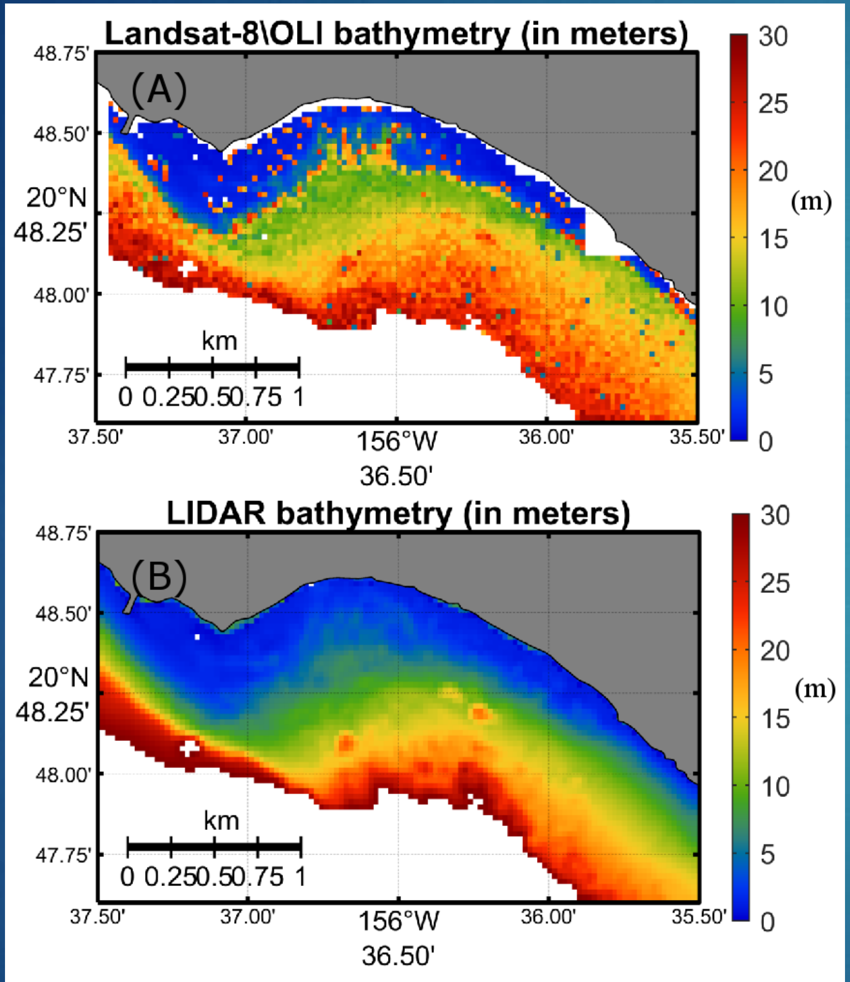




Bathymetry retrieval over coral reefs

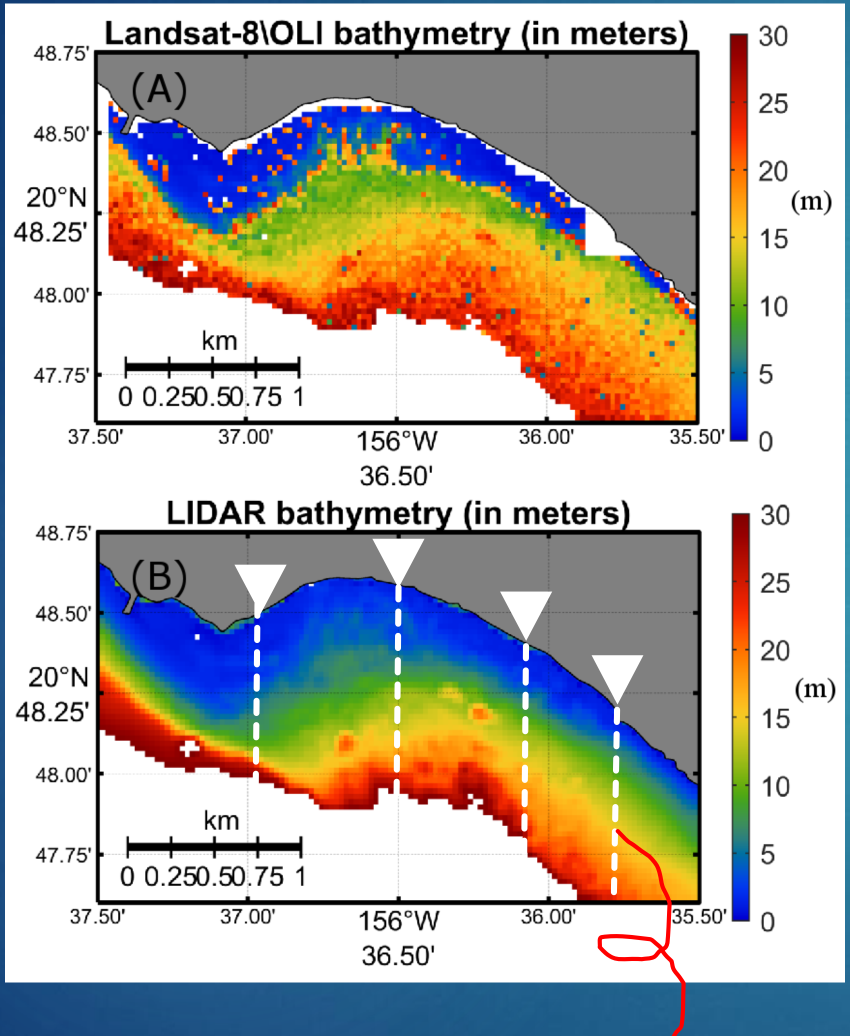
Olowalu Reef, Maui, HI

Bathymetry retrieval over coral reefs

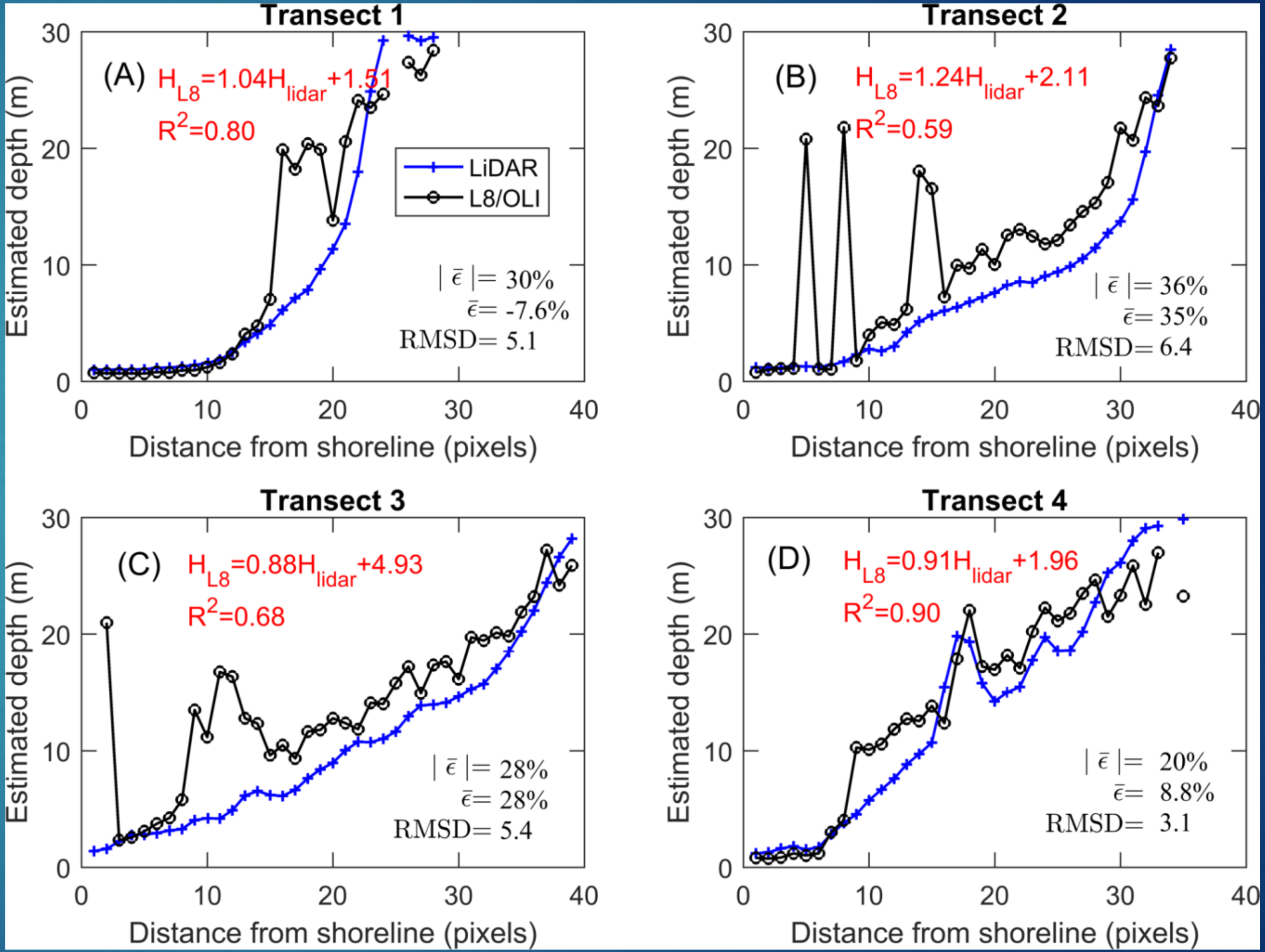


MAPE = 27%

Bathymetry retrieval over coral reefs

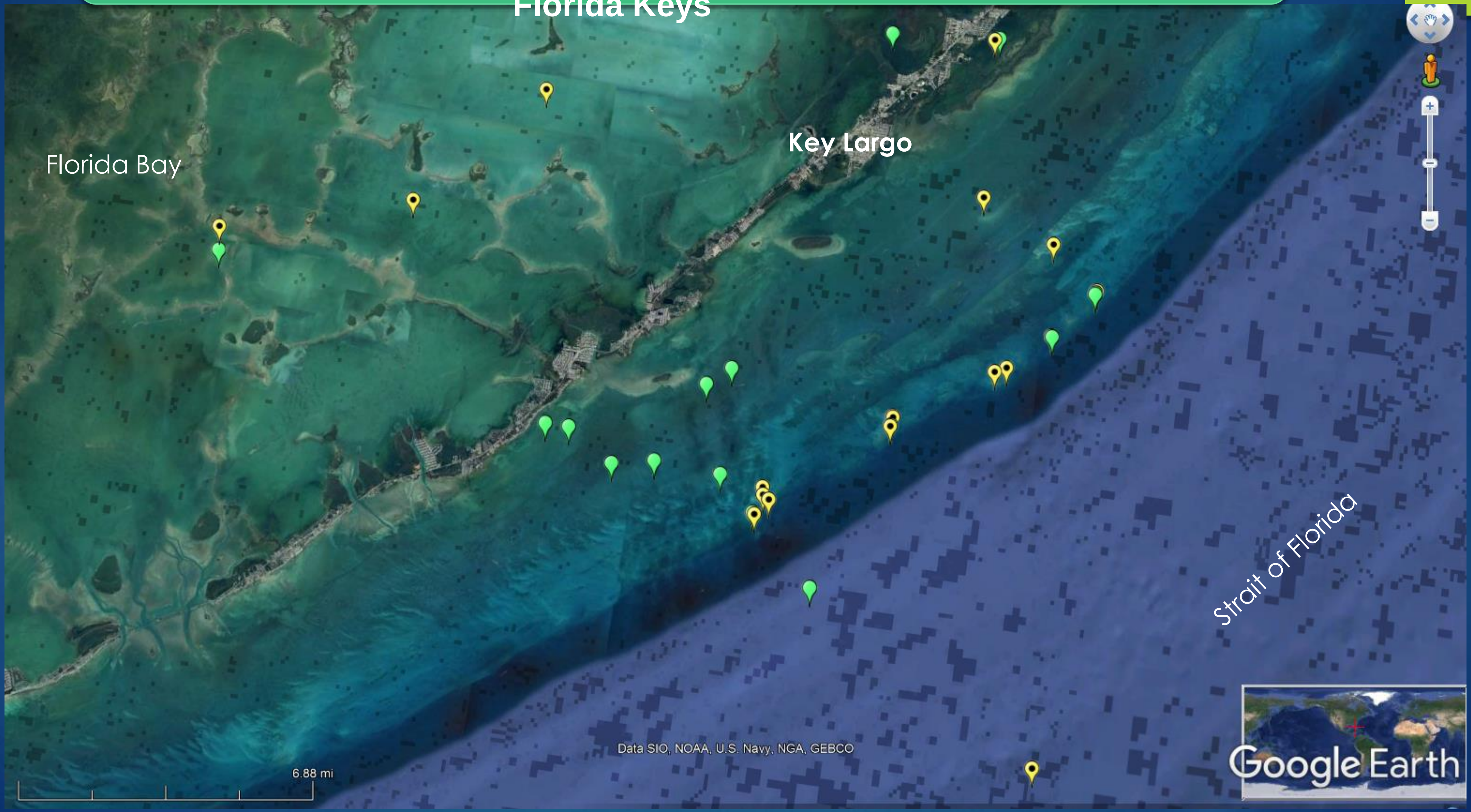


Selected transects

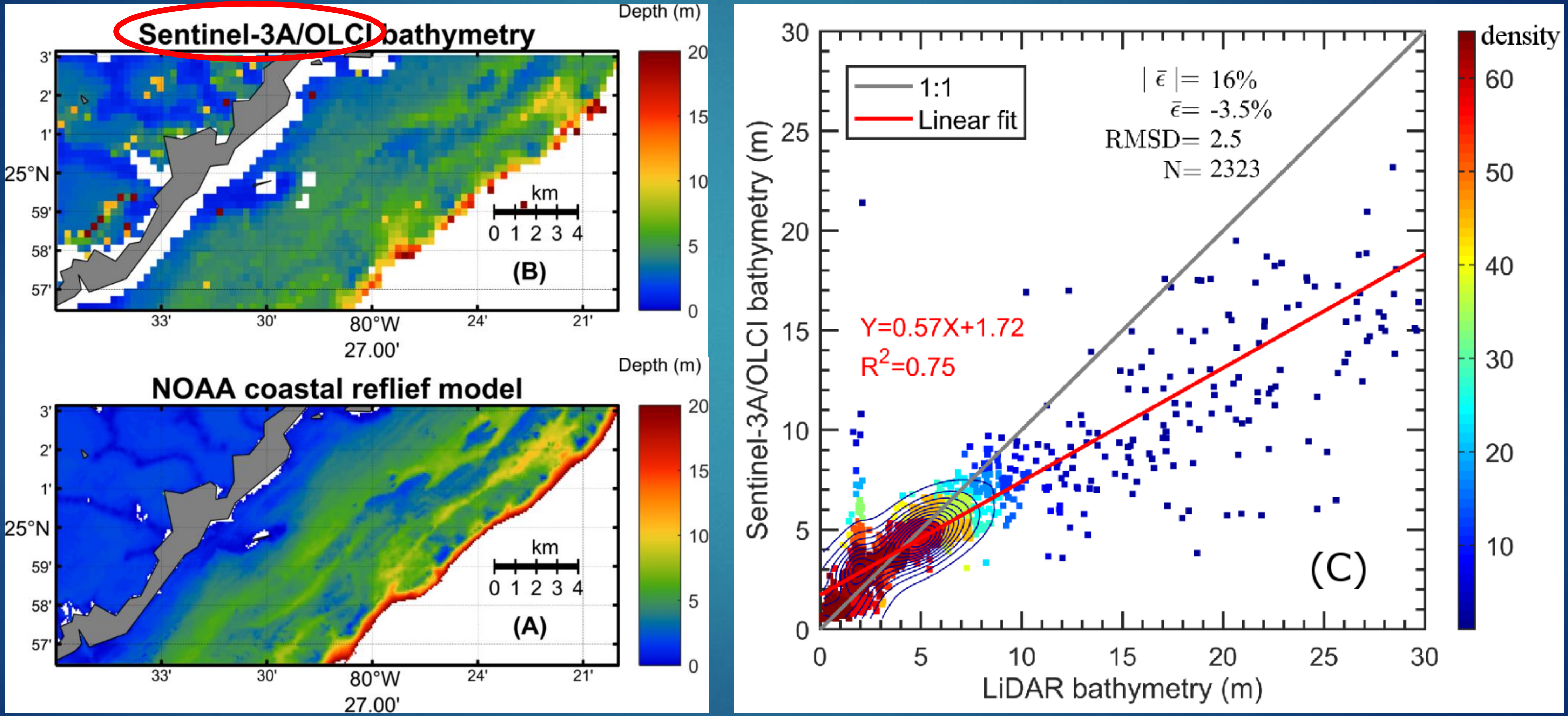


Comparison of model-retrieved depths and LiDAR measurements along four transects

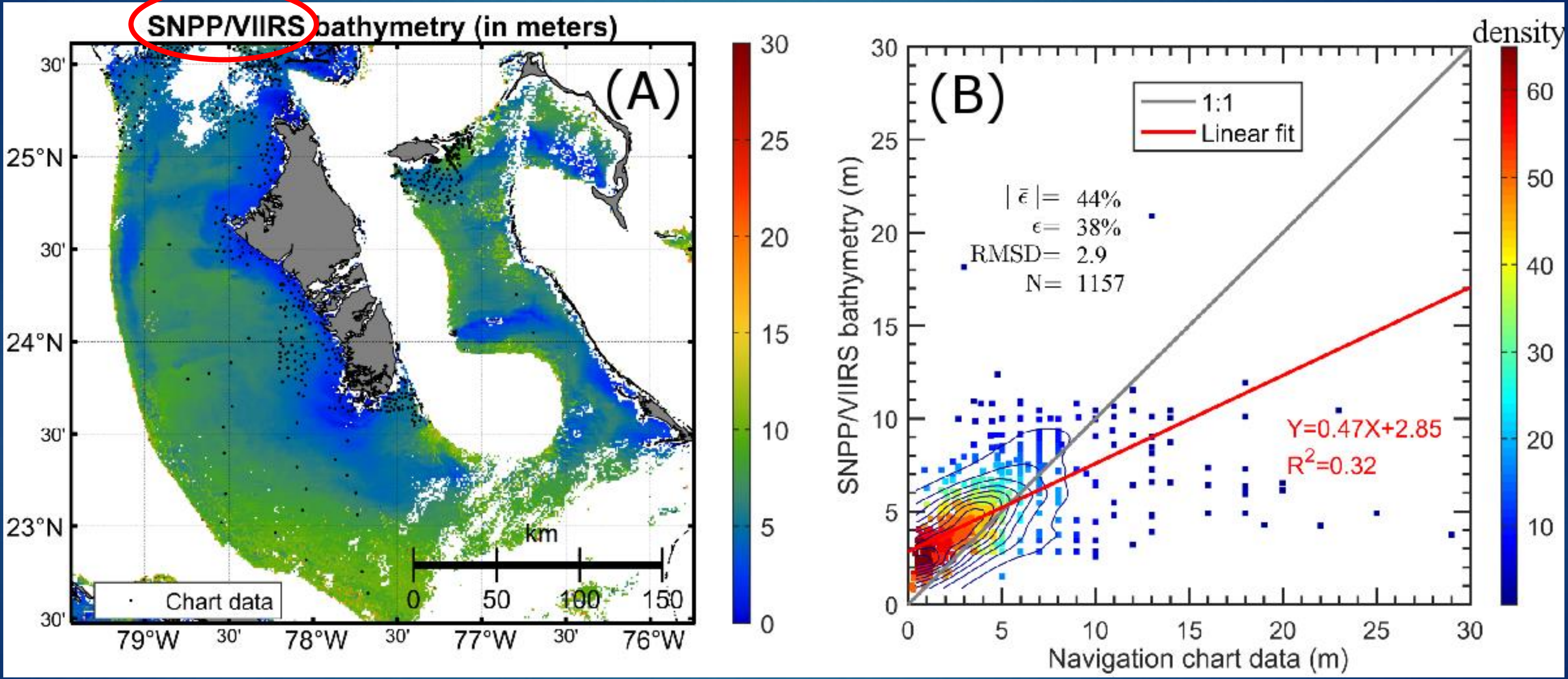
Bathymetry retrieval over seagrass/algae environments



Bathymetry retrieval over seagrass/algae environments



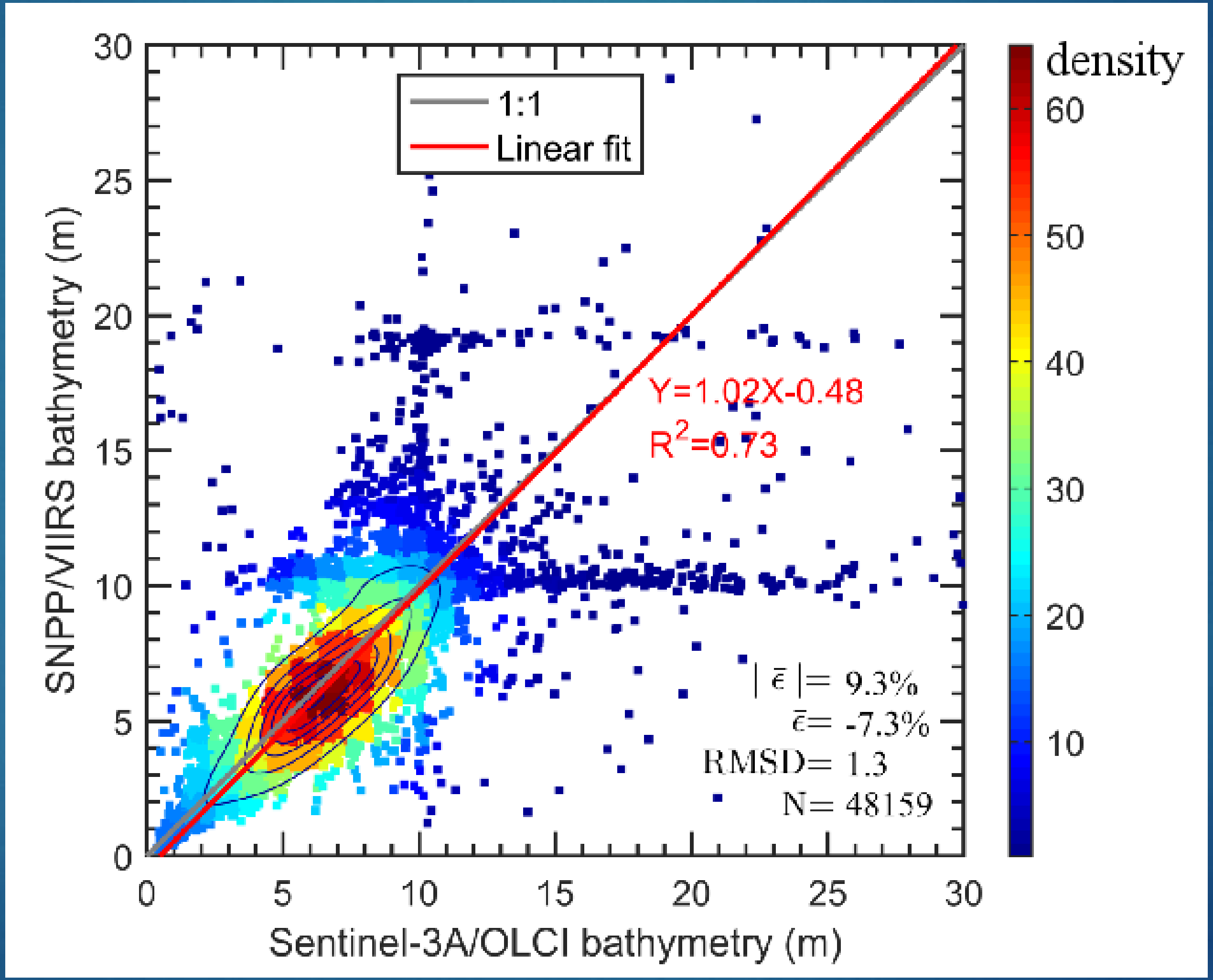
Bathymetry retrieval over sandy environment



The Bahamas

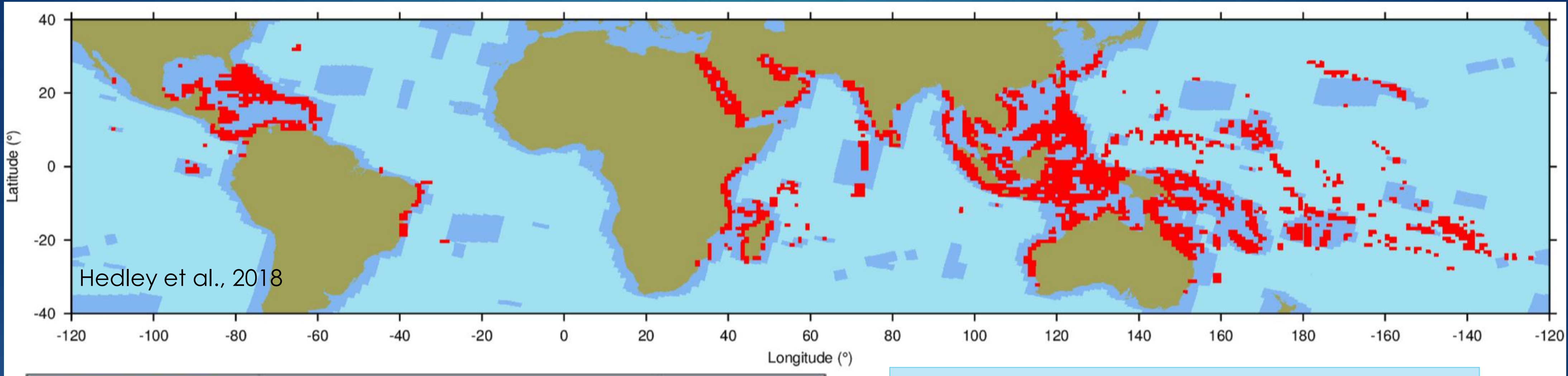
Inter-comparison of bathymetry retrievals from SNPP/VIIRS and Sentinel 3A/OLCI

SNPP/VIIRS

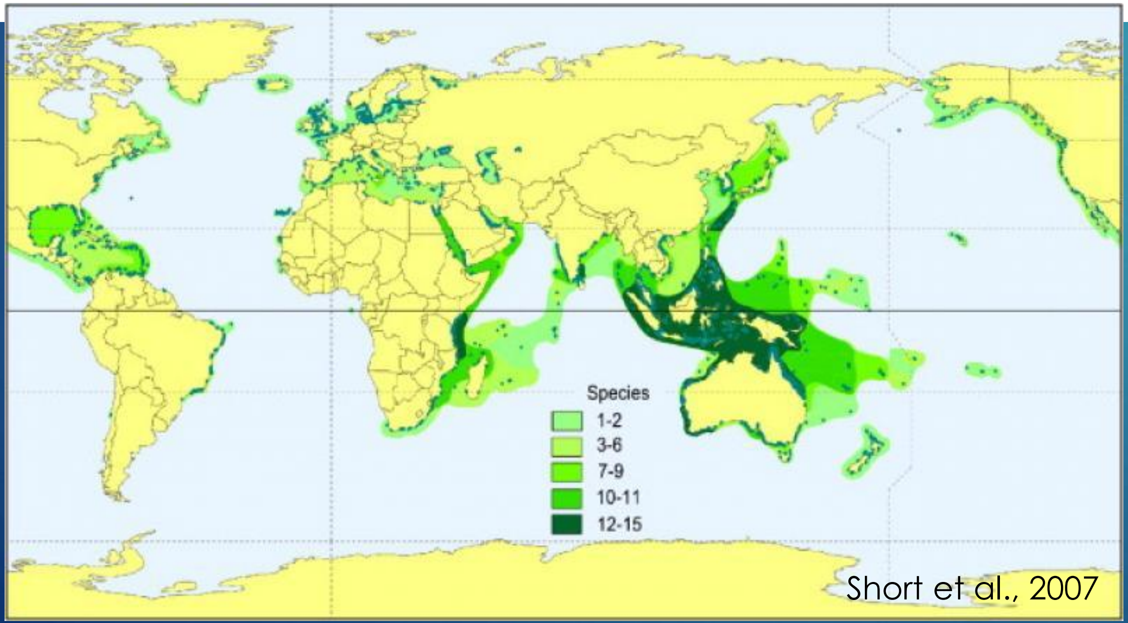


Sentinel 3A/OLCI

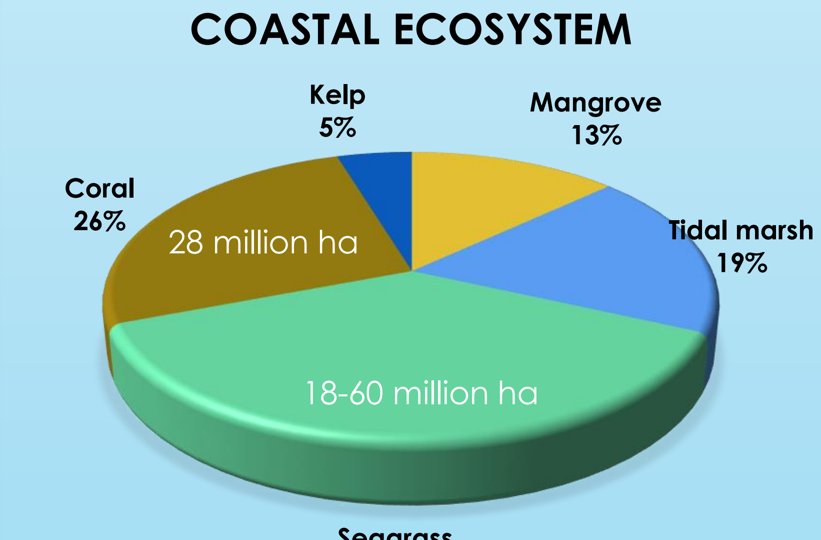
Geographic extent of coral reef and seagrass



Hedley et al., 2018

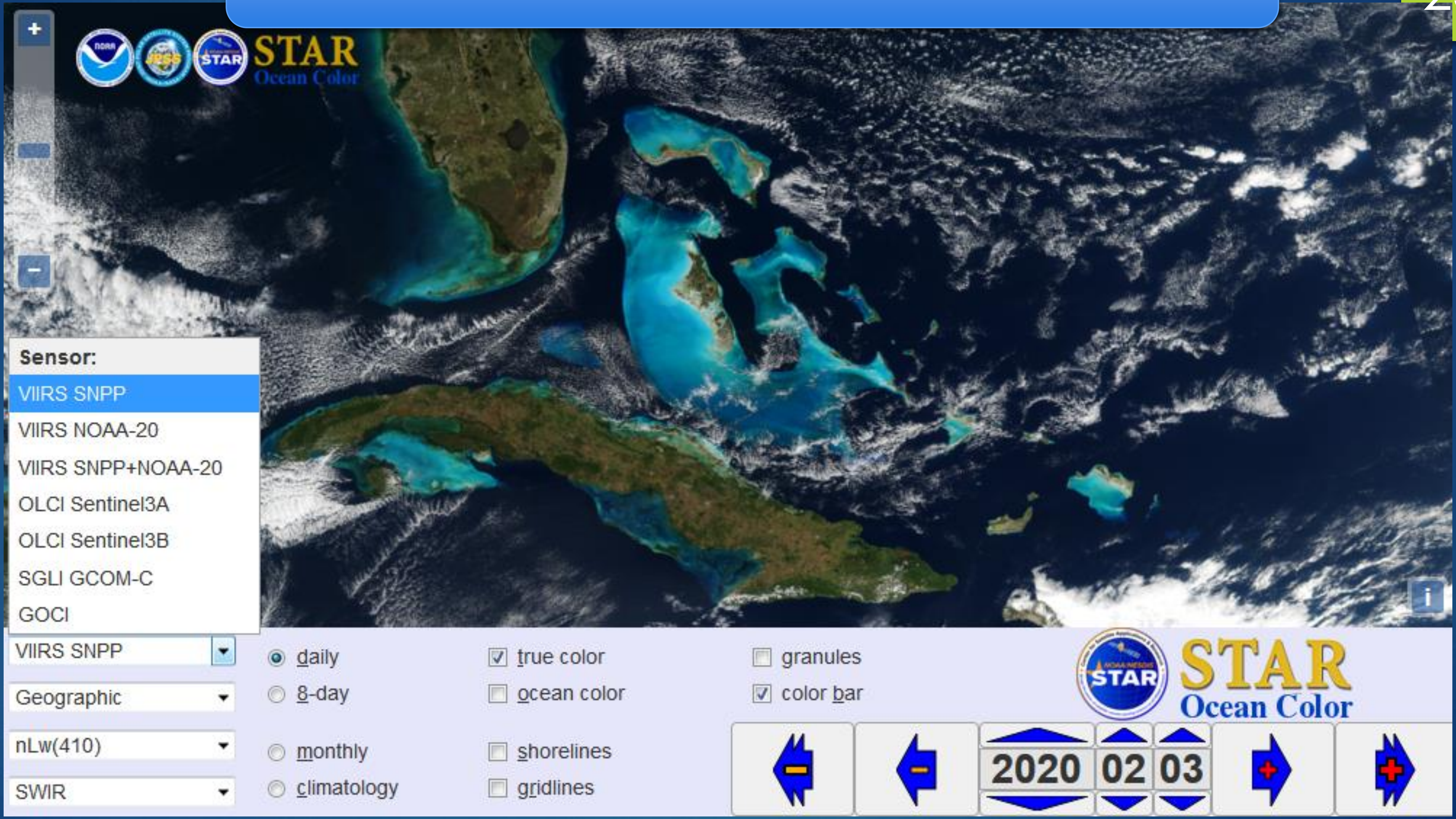


Short et al., 2007



After Howard et al.,(2017)

Satellite ocean color data



All ocean color products are downloadable at OCView and CoastWatch; Currently, no bathymetry product is available.

Summary and future directions

- Satellite ocean color measurements provide an opportunity for mapping the shallow-water bathymetry on synoptic scales and frequently.

- We have developed an semi-analytical algorithm to retrieve the bathymetry map from multi-spectral ocean color images, with applications to SNPP/VIIRS, Sentinel 3A/OLCI, and Landsat 8/OLI.

- Future directions include assessment of depth uncertainties, etc.

- An experimental product of shallow-water bathymetry from VIIRS observations will be generated and evaluated with the availability of funding.

Reference:

Wei, J., Wang, M., Lee, Z.P., Briceño, H.O., Yu, X., Jiang, L., et al. (2020). Shallow water bathymetry with multi-spectral satellite ocean color sensors: Leveraging temporal variation in image data. *Remote Sensing of Environment, 250*, 112035.

Thank you!