Assessing Water Clarity the Chesapeake Bay using Satellite-derived Secchi Disk Depth

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Backgrounds

-. **‘Water Clarity’** or ‘**Water Transparency’** is a key parameter to understand water quality properties and biophysical processes in the aquatic ecosystems, particularly in inland and coastal waters.

-. **‘Water Clarity’** can be significantly affected by phytoplankton, dissolved organic matters, and suspended sediments.

-. **‘Secchi Disk Depth (SDD)’** has been widely used to measure water transparency over 150 years as an easy and low-cost tool. However, Secchi disk measurements are **labor-intensive** and often **spatially & temporally limited** in observation coverages.

-. **Satellite Remote Sensing** data are broadly used as a powerful tool to perform continuous monitoring of water clarity.

Empirical SDD algorithms

'Secchi Disk Depth (SDD)' has been estimated from empirical algorithms between *in situ* SDD measurements and water quality parameters (e.g., water diffuse attenuation coefficient, K_d) and surface reflectance data:

-. Water diffuse attenuation coefficient (K_d)

SDD = 1.44 / K_d , (Kirk, 1995)

-. Surface Reflectance (nL_w, R_{rs})

SDD = 6.4023 · [$nL_w(551)$]$^{-0.7269}$ for Yellow Sea (*Son et al.*, 2005)

1/SDD = 0.0401 + 0.4629 X – 0.360 X^2 + 0.1701 X^3,

where X=R_{rs}(~550) for Great Lakes (*Bingding et al.*, 2015)

SDD = 10^[0.8400 – 0.8639 X – 0.4739 X^2 – 0.5978 X^3] ,

where X= Log[nL_w(551)] for Great Lakes (Son & Wang, 2020)

Semi-Analytical SDD algorithms

Semi-Analytical SDD algorithm has been developed by Lee et al. (2015; 2016) and widely used for the satellite ocean color data.

Since the Lee's SDD algorithm (Lee et al., 2015) is mainly developed for global ocean waters, there are considerable uncertainties in SDD estimates in inland and turbid coastal waters .

Studies have reported the uncertainties and improved Lee's SDD algorithm for optically complex inland and turbid coastal waters (Jia et al., 2022; Jiang et al., 2019; Mao et al., 2018; Qing et al., 2021; Rodrigues et al., 2017; Zeng et al., 2020).

Recently, Xiang et al. (2023) further improved the semi-analytical SDD model for both clear open ocean and extremely turbid nearshore/inland waters, and validated SDD retrievals from various satellite sensors including MODIS and VIIRS.

Objectives

-. Assessment of the proposed semi-analytical algorithm from Xiang et al. (2023) & Wang et al. (2009) estimating SDD (hereafter **CB-SDD**) in the Chesapeake Bay.

-. Construction of long-term satellite-derived SDD composites from MODIS-Aqua and VIIRS-SNPP data using CB-SDD algorithm to describe spatial and temporal variations in water transparency in the Chesapeake Bay.

-. Comparison between timeseries of *in situ* water quality monitoring data and satellite-derived SDD products to investigate seasonal and interannual variations in the Chesapeake Bay.

Proposed Semi-Analytic SDD Model

-. Semi-Analytic SDD model for clear & turbid waters (Xiang et al., 2023)

$$Z_{SD} = \frac{1}{2.5 \cdot Min\left(K_d(\lambda)\right)} \cdot ln\left(\frac{\left|0.14 - R_{rs}^{pc}\right|}{0.013}\right)$$

where

$\boldsymbol{Min(K_d(\lambda))}$ is the minimum $K_d(\lambda)$ of 4 or 5 bands (443, 490, 532, 555, & 670 nm)

$\boldsymbol{R_{rs}^{pc}}$ is $R_{rs}(\lambda)$ at the corresponding band of Min($K_d(\lambda)$)

-. $K_d(443) = 1.2028 \times K_d(490) + 0.0557$

-. $K_d(532) = 0.8192 \times K_d(490) + 0.0207$

-. $K_d(554) = 0.7418 \times K_d(490) + 0.0331$

-. $K_d(670) = 0.5652 \times K_d(490) + 0.5912$

-. $\boldsymbol{K_d(490)}$ is calculated using Wang et al. (2009)

DATA

*. **In-situ** data

-. Secchi disk depth measurements from Chesapeake Bay Program Office
  : 84 stations (CB, EE, LE, RET, WE; 2002-2023)
  : total no. (26,670); MODIS-Aqua (25,230), VIIRS-SNPP (14,702)

*. **Satellite Ocean Color** Data

-. Chl-a, $R_{rs}(\lambda)$

-. MODIS-Aqua level-2 (2002-2022) – 11,188 files

-. VIIRS-SNPP level-2 (2012-2023) – 8,021 files

-. Derived $K_d(490)$ & SDD using Wang et al. (2009) and Xiang et al. (2023)

-. Remapped / generated composite images

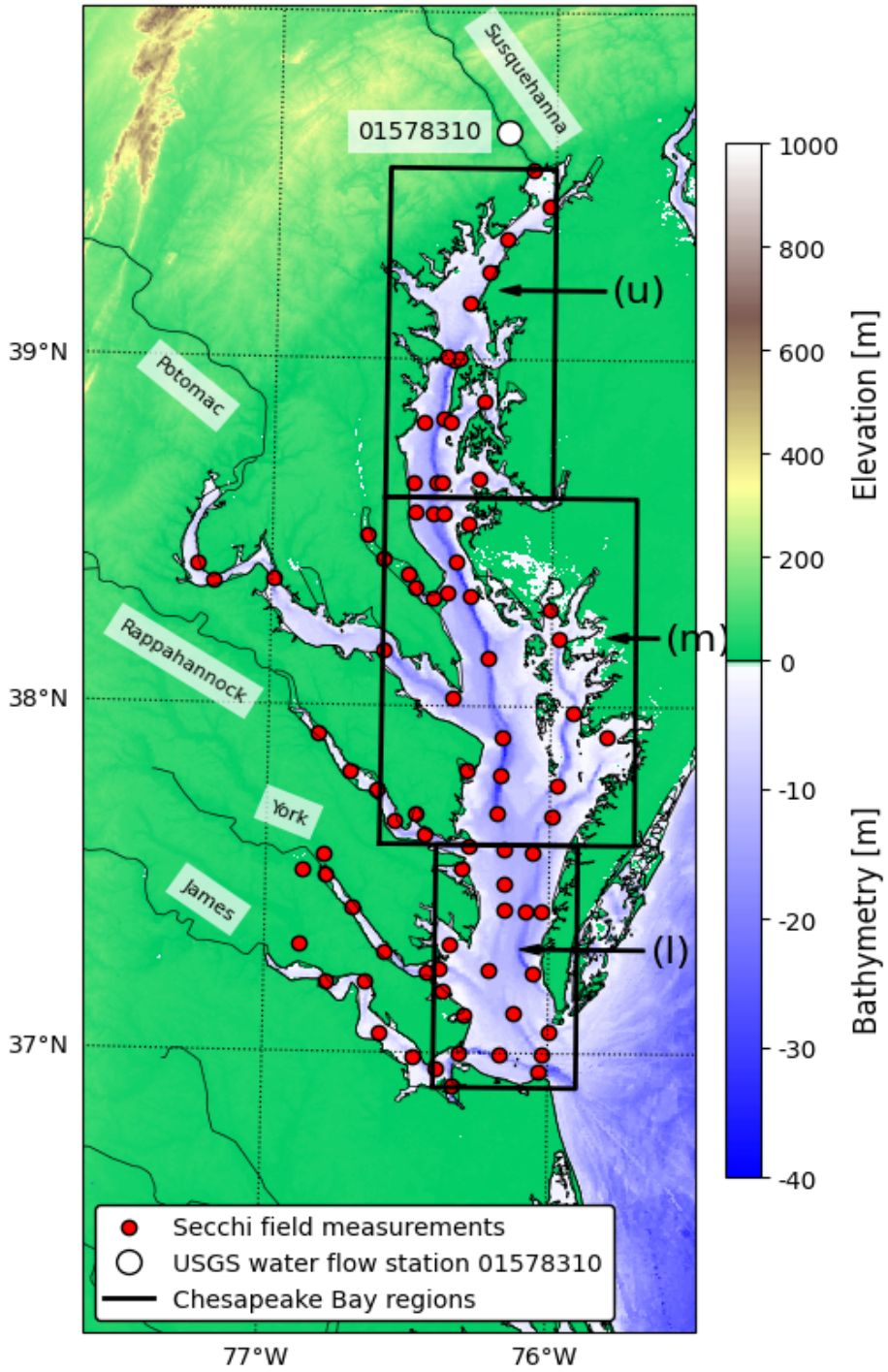
*. **Matchup** Comparison (Wang et al., 2009)

-. Applied 3 L2_flags (high solar/sensor zenith angles & sun glint)

-. Extracted 3×3 & 5×5 pixels around in-situ locations

-. Comparisons in multiple time differences between satellite & in-situ data

Study Map



Map of **Chesapeake Bay** including

-. **Water depth** and Terrain (color shading)

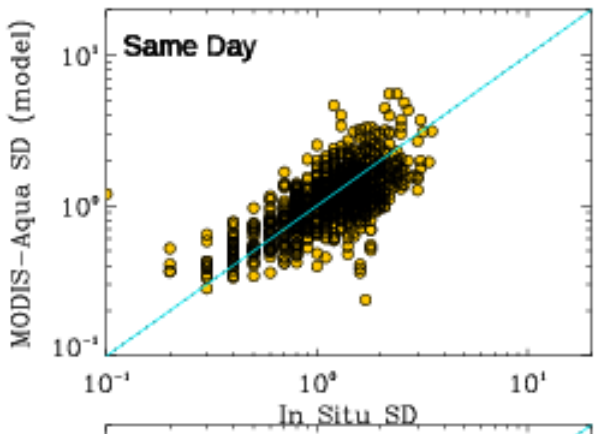
-. Location (white circle) of the **USGS station** 01578310 for the Susquehanna **River flow**

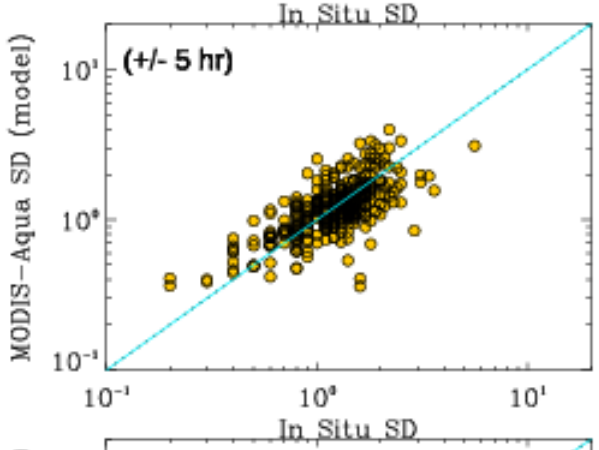
-. Locations (red circles) **of 84 stations** for **SDD measurements** during 1984–2023 from the Chesapeake Bay Program.

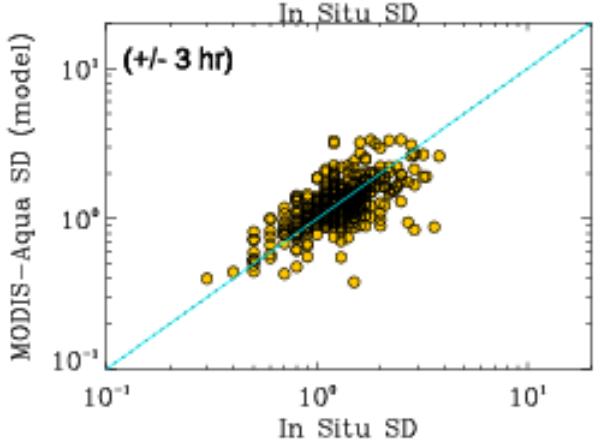
-. **3 Sub-areas** (black boxes): (u) Upper, (m) Middle, and (l) Lower Bay for time series analysis.

MODIS-Aqua *SDD_model* vs *SDD_env*

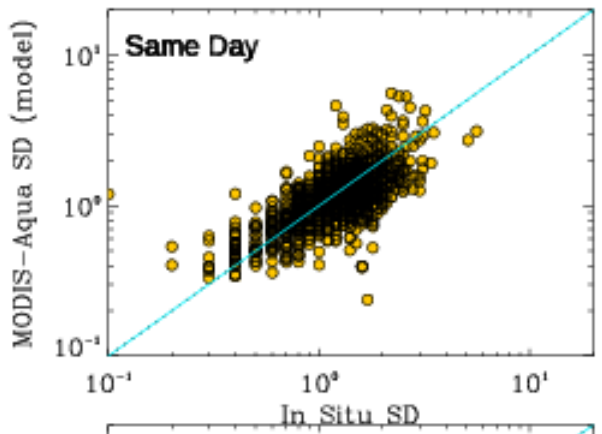
(3x3 pixels)

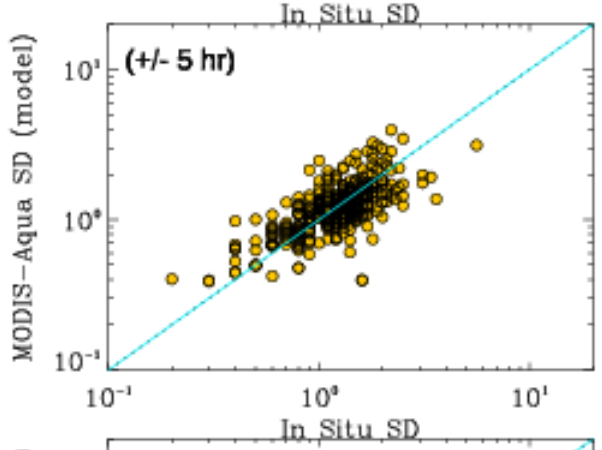


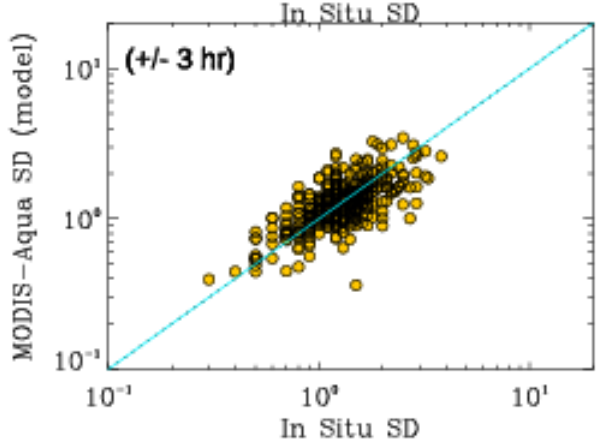




(5x5 pixels)

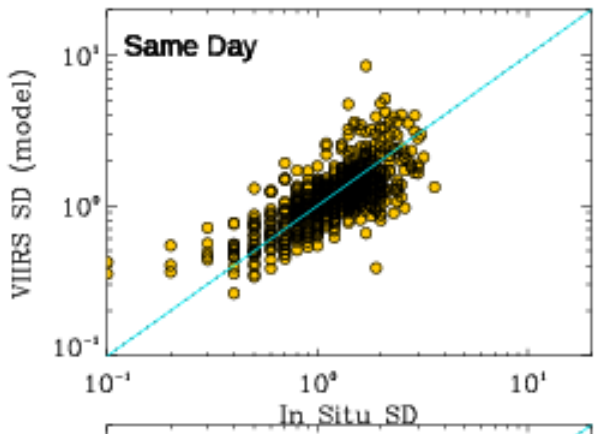


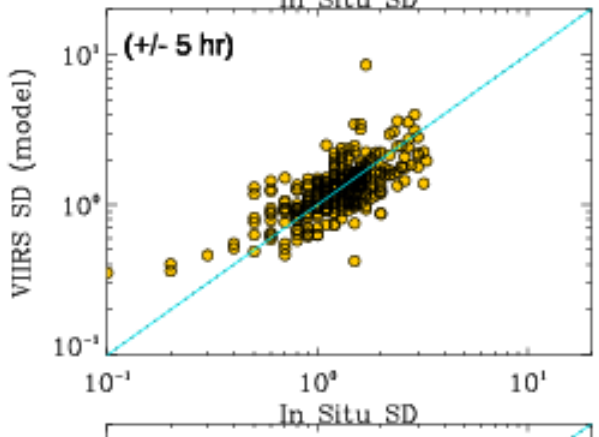


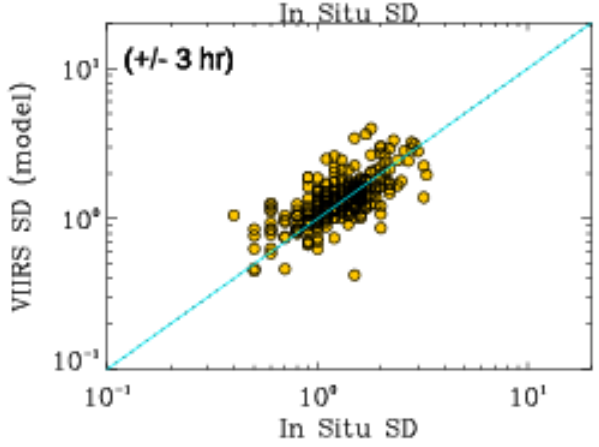


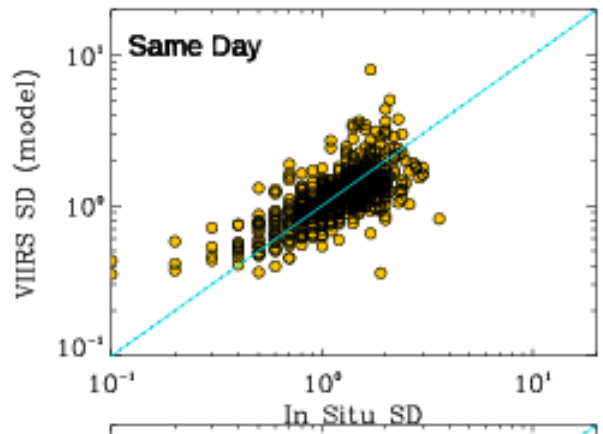
VIIRS-SNPP *SDD_model* vs *SDD_env*

(3x3 pixels)

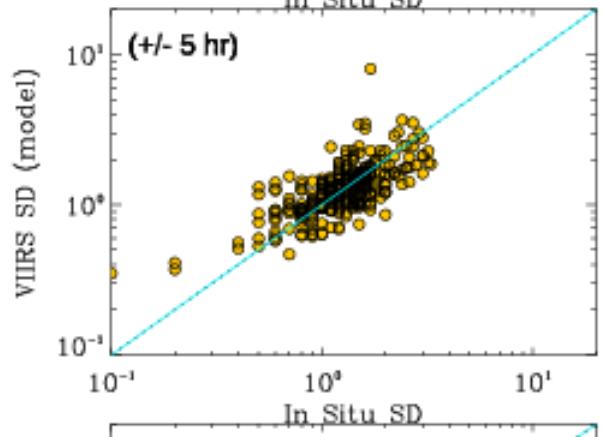


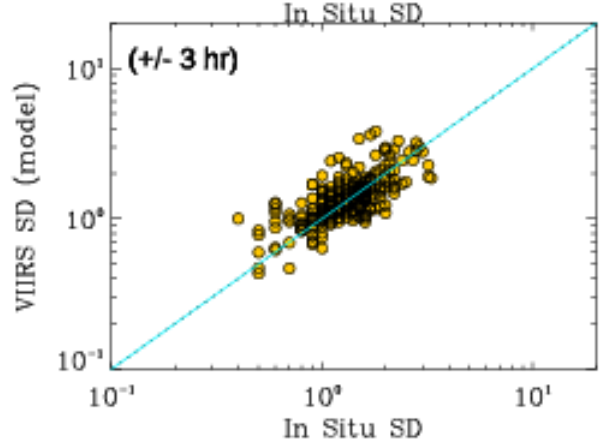






(5x5 pixels)



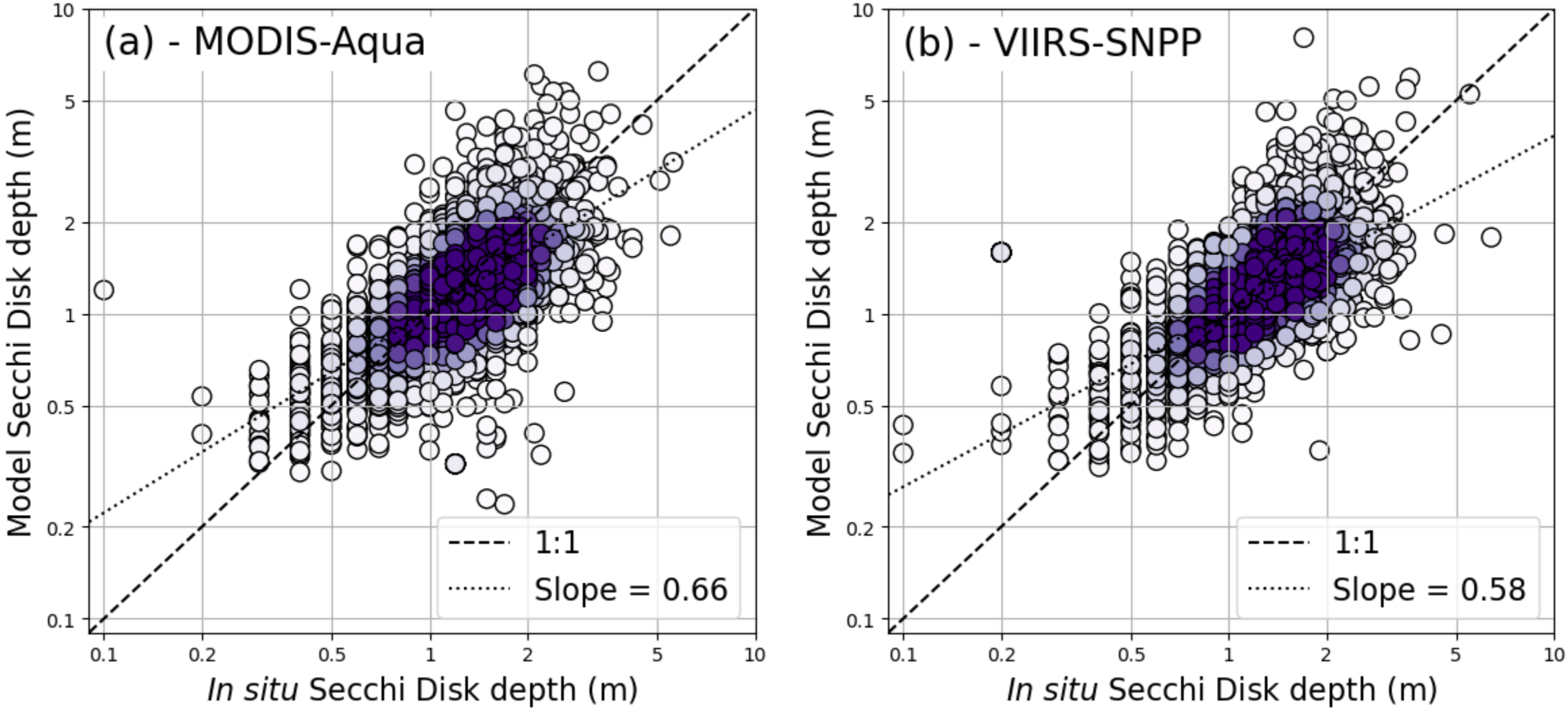


Statistics of the correspondence between *in situ* SDD and satellite-derived SDD

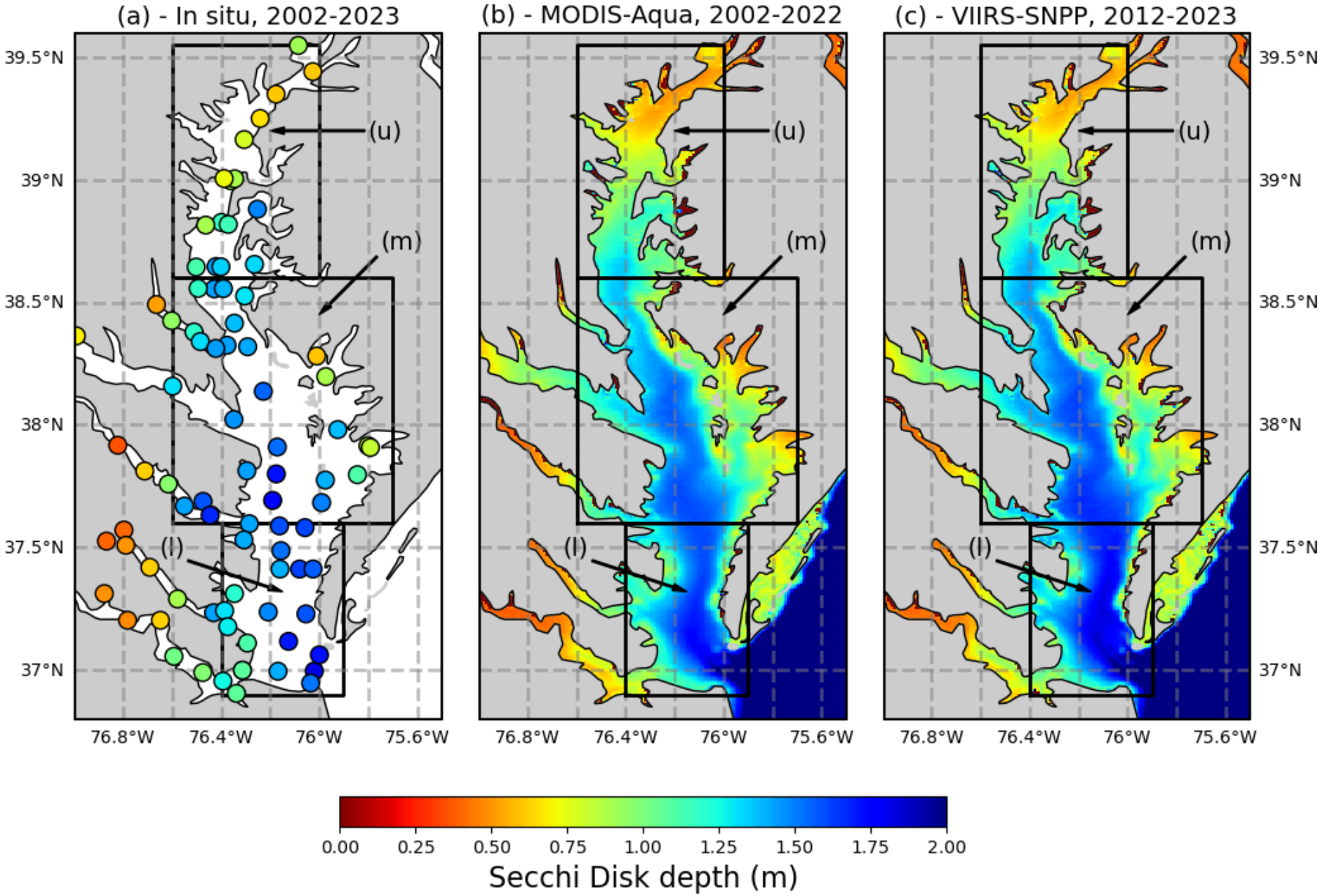
Satellite Sensor	Box size	Match-up period	No	Correlation between log_{10}-transformed satellite SDD and log_{10}-transformed in-situ SDD					Pairwise comparison using the ratio (Satellite SDD / in-situ SDD)		
				MMB	MAE	R^2	RMSE	S	AVG	MED	STD
MODIS-Aqua	3×3	Same day	4839	0.939 (-6%)	1.286	0.325	0.147	0.994	0.994	0.945	0.415
MODIS-Aqua	3×3	±5 hours	1204	0.998 (0%)	1.242	0.388	0.131	0.950	1.041	1.007	0.301
MODIS-Aqua	3×3	±3 hours	406	0.999 (0%)	1.242	0.329	0.131	0.973	1.044	1.003	0.312
MODIS-Aqua	5×5	Same day	4717	0.940 (-6%)	1.280	0.325	0.143	0.986	0.991	0.944	0.361
MODIS-Aqua	5×5	±5 hours	1188	1.001 (0%)	1.236	0.407	0.127	0.932	1.043	1.008	0.295
MODIS-Aqua	5×5	±3 hours	397	1.001 (0%)	1.229	0.408	0.123	0.955	1.041	1.004	0.292
VIIRS-SNPP	3×3	Same day	3853	0.974 (-3%)	1.291	0.313	0.156	0.936	1.050	0.980	0.587
VIIRS-SNPP	3×3	±5 hours	1053	1.053 (+5%)	1.233	0.377	0.131	0.944	1.102	1.015	0.367
VIIRS-SNPP	3×3	±3 hours	406	1.085 (+8%)	1.226	0.176	0.133	1.023	1.136	1.048	0.373
VIIRS-SNPP	5×5	Same day	3651	0.983 (-3%)	1.275	0.338	0.149	0.901	1.056	0.982	0.591
VIIRS-SNPP	5×5	±5 hours	1004	1.055 (+6%)	1.228	0.430	0.125	0.925	1.100	1.039	0.348
VIIRS-SNPP	5×5	±3 hours	395	1.082 (+8%)	1.210	0.318	0.120	0.977	1.123	1.042	0.330

MMB–Multiplicative Mean Bias; MAE–Mean Absolute Errors

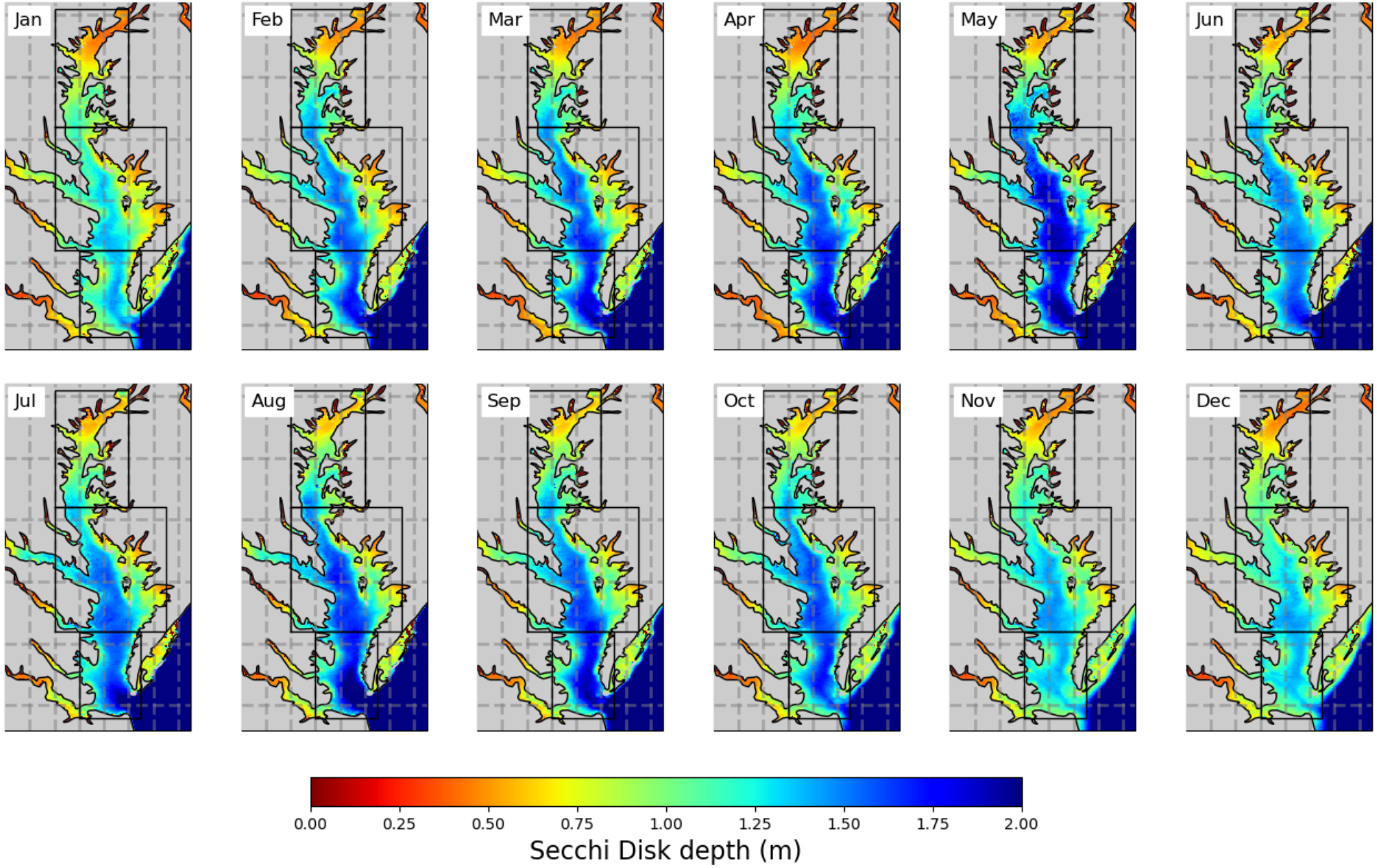
- All correlations have very small bias within ±8%
- Best accuracy (min. MAE) for both MODISA and VIIRS are for 5x5 pixel boxes and time window ±3 hours



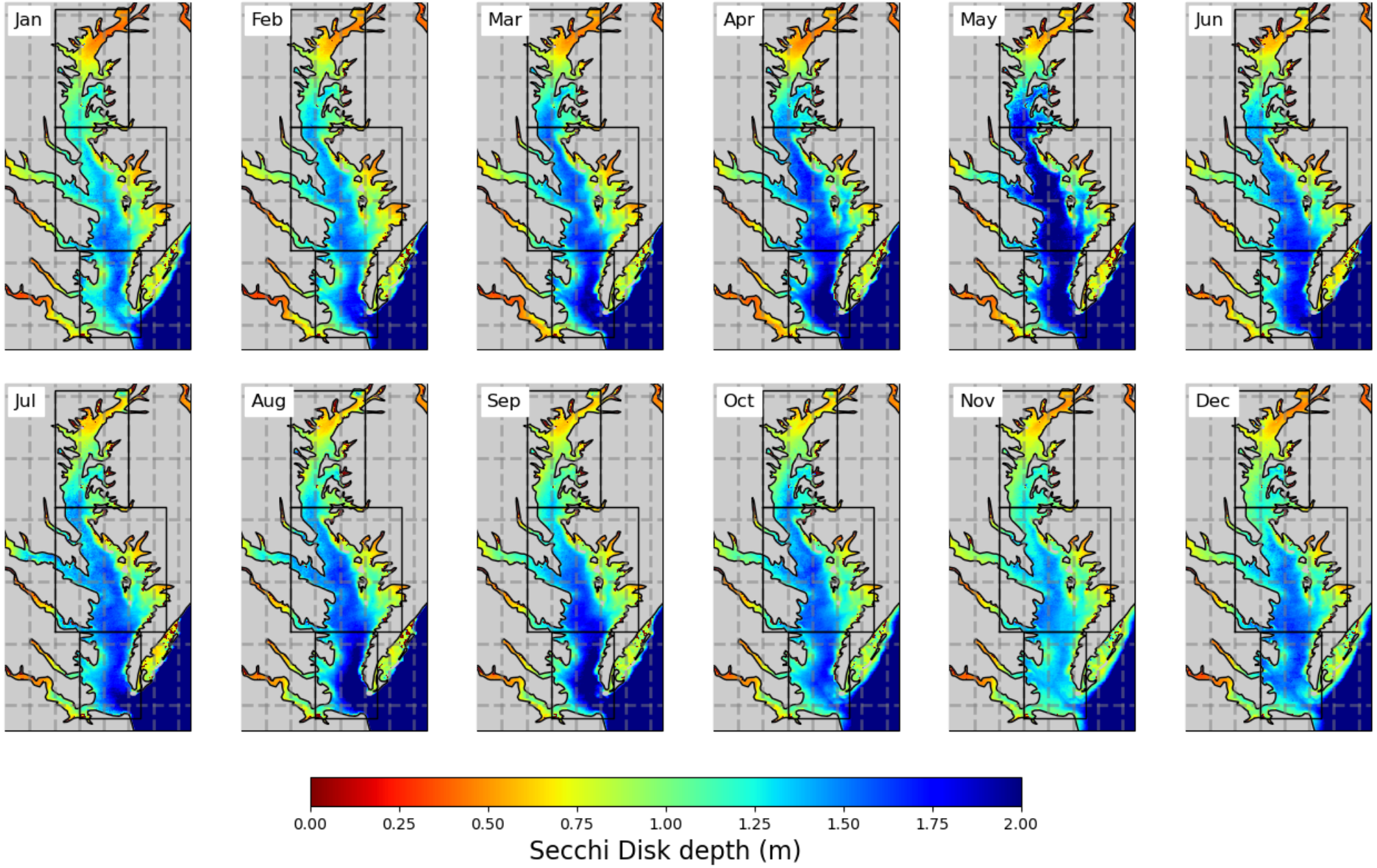
Density Plots between measured *in situ* Secchi Disk depths (SDD) and satellite-derived SDD using CB-SDD from (a) MODIS-Aqua and (b) VIIRS-SNPP data (Matchups on the same day and in 5x5 pixel boxes).



(a) Mean Secchi Disk Depths for *in situ* measurements (2002–2023) and climatology SDD composites of (b) MODIS-Aqua (2002–2022) and (c) VIIRS-SNPP (2012–2023) in the Chesapeake Bay.

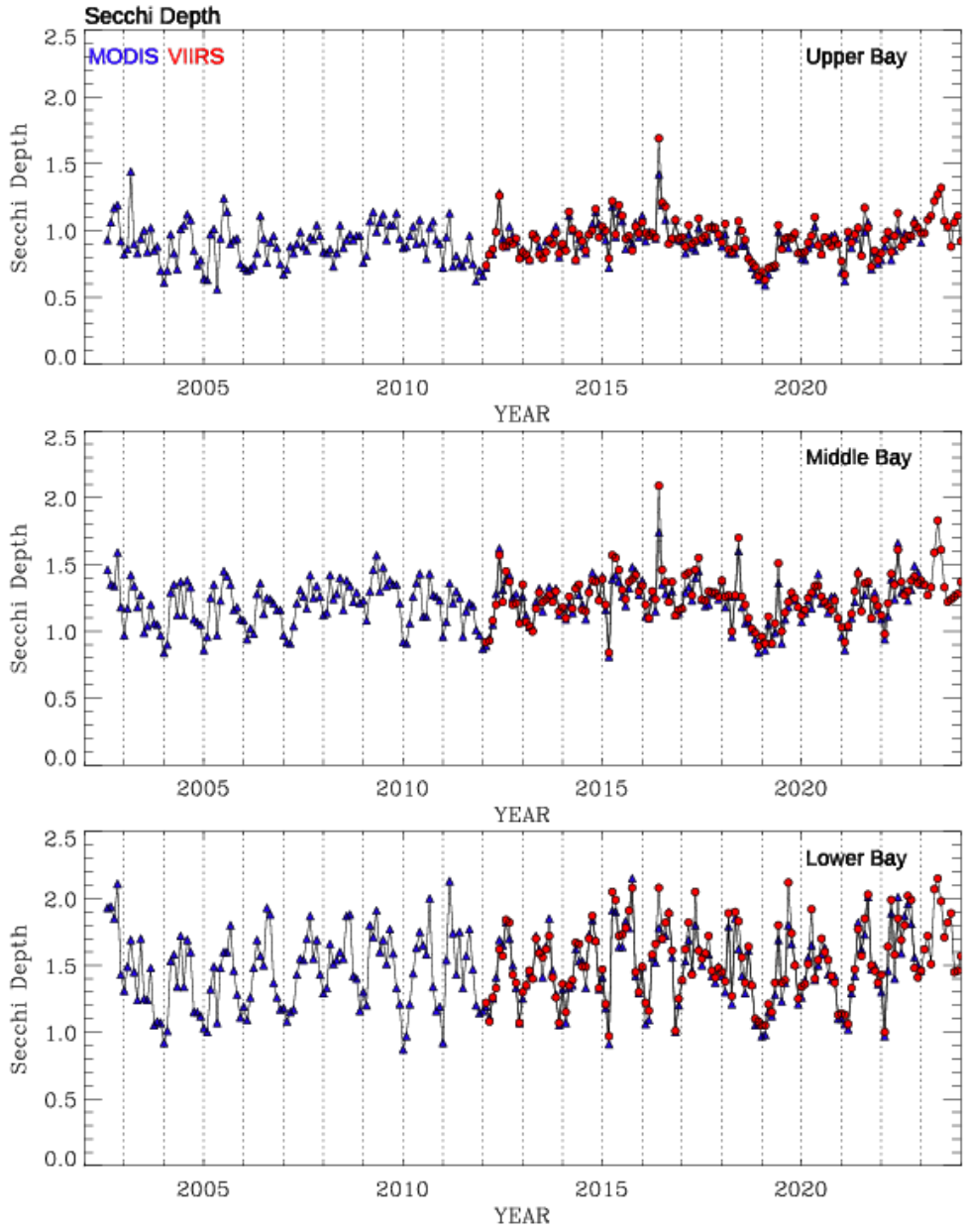


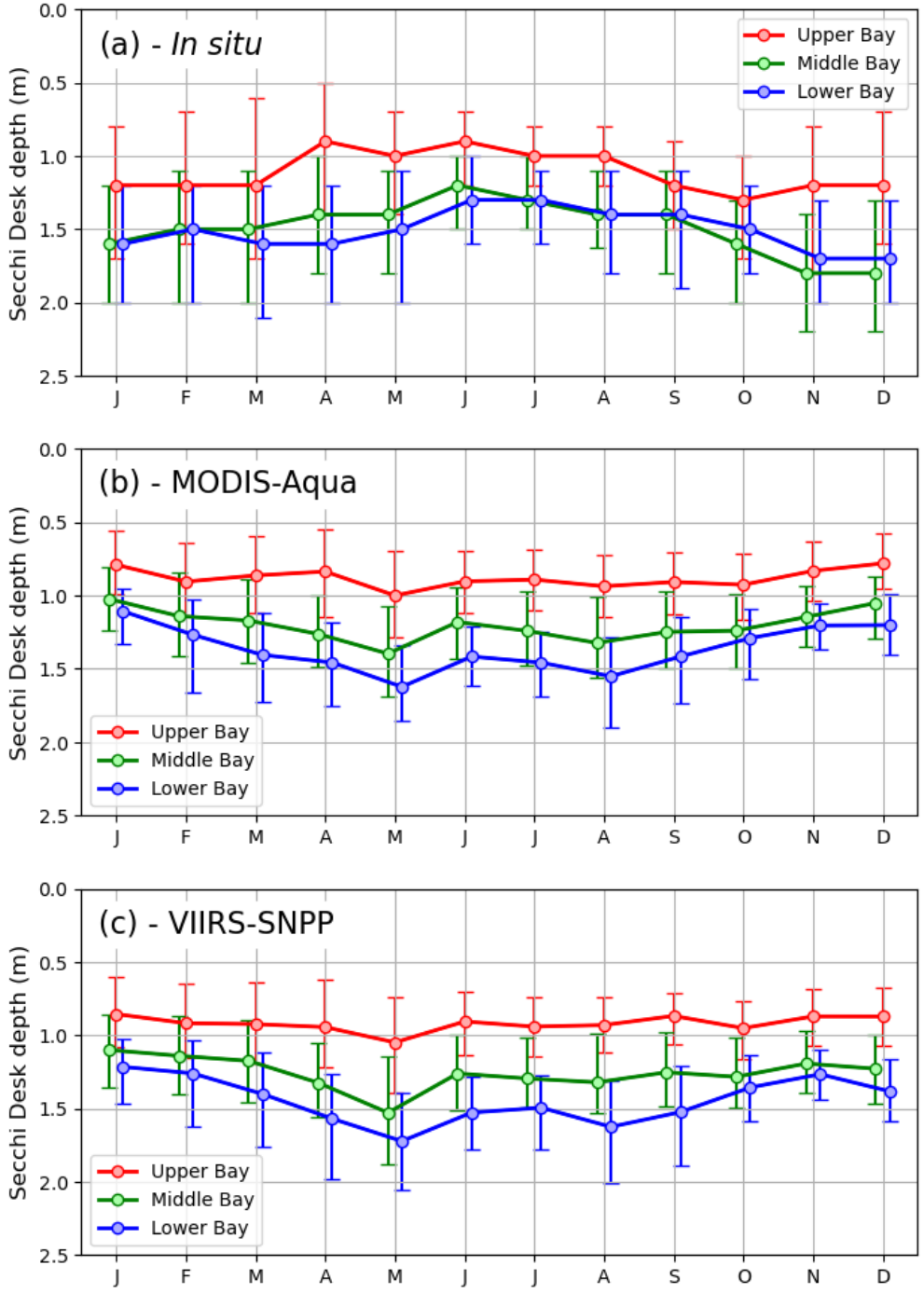
Monthly climatology (**2002–2022**) composite images of **Secchi Disk Depth** from **MODIS-Aqua** in the Chesapeake Bay.



Monthly climatology (**2012–2023**) composite images of **Secchi Disk Depth** from **VIIRS-SNPP** in the Chesapeake Bay.

Timeseries of MODIS-Aqua & VIIRS-SNPP Monthly SDD





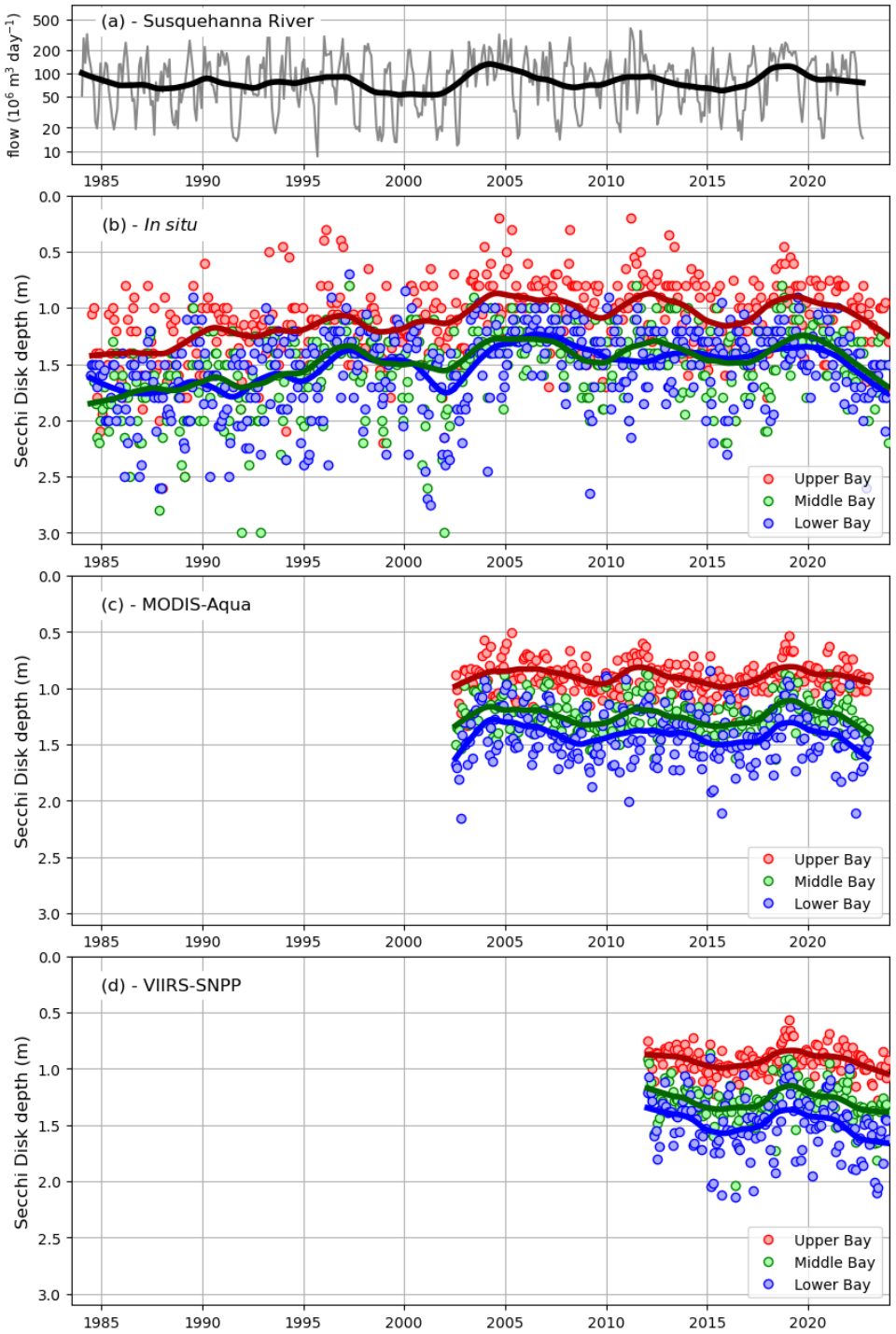
- Seasonal variations of satellite-derived SDD were very similar in both MODIS and VIIRS, but somewhat different from that of *in situ* SDD. Satellite SDD values were also shallower than *in situ* SDD.

- *In situ* SDD over the three regions was deeper in winter and shallower in spring to summer, while the satellite SDD was shallower in winter.

- *In situ* SDD is shallowest in April–June in Upper Bay and in June in Middle & Lower Bays, while satellite SDD is shallowest in winter and deeper in May and August.

- These differences are likely due to variations in the density of *in situ* sampling stations across different parts of the Bay.

Time series of climatology monthly averages of **Secchi Disk Depth** in Upper (**red**), Middle (**green**), and Lower (**blue**) Chesapeake Bay regions from **(b) *in situ*** measurements (1984–2023), **(b) MODIS-Aqua** (2002–2022), and **(c) VIIRS-SNPP** (2012–2023).



- Water transparency in the Chesapeake Bay was decreasing during 1984-2005.
- Interannual variations of SDD (*in situ* and modeled from both satellites) are regulated by Susquehanna River discharge (maxima in 2004, 2012 and 2019).
- The range of variations of satellite-modeled SDD not as wide as the range of variations of *in situ* SDD

Interannual variations of **(a) Susquehanna River flow** (1984–2023), and Water Transparency (**Secchi Disk Depth**) from **(b) *in situ* measurements** (1984–2023), **(c) MODIS-Aqua** (2002–2022), and **(d) VIIRS-SNPP** (2012–2023) in **Upper** (**red**), **Middle** (**green**), and **Lower** (**blue**) regions of the Chesapeake Bay. Solid lines–***time series smoothed with LOESS***.

Summary

-. The proposed semi-analytical SDD (CB-SDD) algorithm for the Chesapeake Bay was extensively evaluated and performs well for MODIS-Aqua & VIIRS-SNPP data over Chesapeake Bay.

-. Satellite-derived SDD maps were generated using the CB-SDD algorithm to investigate spatiotemporal variations of water clarity in Chesapeake Bay.

-. Seasonal and interannual variation in SDD are evident in the entire Chesapeake Bay. Results reveal that seasonal and interannual variations of river discharge are similar to those from SDD measurements.

-. Our results show that satellite data and this method can be considered to extend water quality observations where and when *in situ* observations are lacking in the Bay.