CDM Spectral Slope Inversion from the UV-Visible Ocean Color

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1. Questions & hypotheses

Unique features are observed in the remote sensing reflectance spectra (350-700 nm) in the oceans. The observation of different behaviors of R_{rs} between at UV bands and visible bands has inspired this study (Fig. 1).

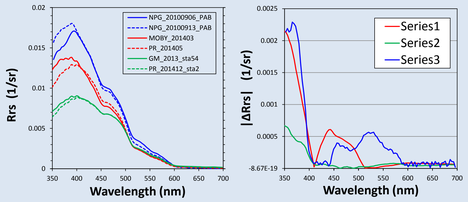


Fig.1 Hyperspectral R_{rs} measured in the Pacific, Atlantic, and GoMex.

- Our first hypothesis is that the spectral slopes of CDOM and detrital matters are largely responsible for the enlarged difference of R_{rs} in the UV bands.
- Further, addition of UV bands to the ocean color will improve the retrievals of the spectral slopes of CDOM and detrital matters.

2. R_{rs} sensitivity to varying spectral slopes

Two oceanic waters are examined of CHL = 0.07 and 0.15 mg m^{-3}. The water inherent optical properties are modeled as functions of CHL with $a_{ph}(440) = 0.05 \times [CHL]^{0.626}$, (Bricaud et al., 1995), then $a_{ph}(\lambda) = a_{ph}(440) \times a_{ph}^{*}(\lambda)$, and $b_{bp} = \alpha[CHL]^{\beta}$, (Huot et la., 2008). The R_{rs} is modeled with Hydrolight 5.0.

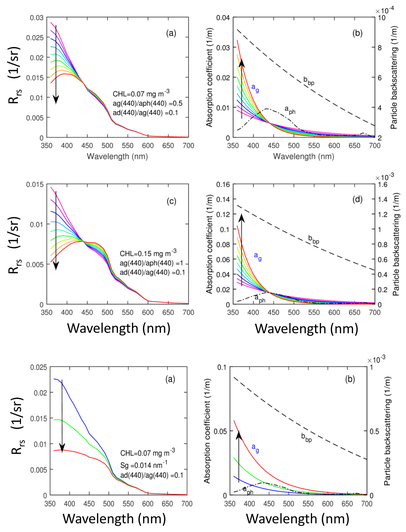


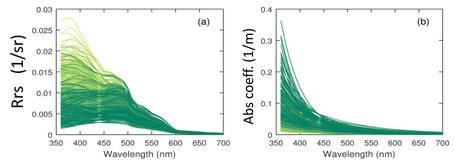
Fig.2 Variation of R_{rs} spectra shapes with different spectral slopes of CDOM in two oceanic waters. The spectral $a_g(\lambda)$ is denoted in colored lines, $a_{ph}(\lambda)$ in black dash-dot line, and $b_{bp}(\lambda)$ in black dash line. The CDOM slope, S_g increases from 0.008 to 0.024 nm^{-1}.

Fig.3 Variation of R_{rs} spectra shapes with the amplitude of CDOM absorption $a_g(440)$. S_g = 0.014 nm^{-1}. $a_g(440)/a_{ph}(440)$ increases from 0.2, 1, to 2.

3. Inversion of CDM spectral slopes

- **Data**

  Hyperspectral R_{rs} spectra spanning the UV and visible domain (360-700 nm) are simulated by Hydrolight 5, with IOPs synthesized based on IOCCG (2006).



- **Inversion algorithms**

  The Hyperspectral Optimization Process Exemplar (HOPE) (Lee et al. ,1998) is refined for the deep waters, with five unknowns including $a_{ph}(440)$, $a_{dg}(440)$, $b_{bp}(440)$, η and S_{dg}. Specifically, the following models are used:

a_{ph} model: $a_{ph}(\lambda) = \left[a_0 + a_1 \ln a_{ph}(440)\right] \cdot a_{ph}(440)$ (Lee et al., 1999)

a_{dg} model: $a_{dg}(\lambda) = a_{dg}(440)\exp\left[-S(\lambda - 440)\right]$

b_{bp} model: $b_{bp}(\lambda) = b_{bp}(440)\left(\lambda/440\right)^{\eta}$

r_{rs} model: $r_{rs}(\lambda) = G_w \dfrac{b_{bw}(\lambda)}{a(\lambda)+b_b(\lambda)} + G_p(\lambda)\dfrac{b_{bp}(\lambda)}{a(\lambda)+b_b(\lambda)}, \quad G_p(\lambda) = G_0\left[1 - G_1\exp\left(-G_2\dfrac{b_{bp}(\lambda)}{a(\lambda)+b_b(\lambda)}\right)\right]$ (Lee et al., 2004)

Cost function: $Err = \sum_{i=1}^{N}\left(R_{rs}^{\,est}(\lambda_i) - R_{rs}^{\,0}(\lambda_i)\right)^2 \Big/ \sum_{i=1}^{N} R_{rs}^{\,0}(\lambda_i)^2$

- **Evaluation of model estimations**

  The model estimated CDM spectral slopes, S_{dg}, from the R_{rs} with both UV and visible bands (360-700 nm), has shown great improvements, compared with the estimations from R_{rs} with only the visible bands (410-700 nm).

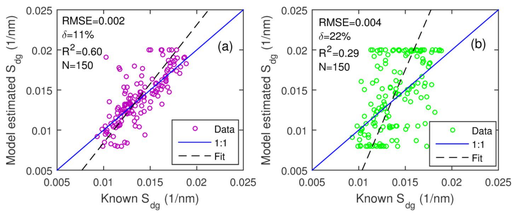


Fig.5(a). Estimated spectral slopes of CDM from the hyperspectral reflectance at all available wavelengths from 360 nm to 700 nm.

Fig.5(b). Estimated spectral slopes of CDM from the hyperspectral reflectance between 410 nm to 700 nm.

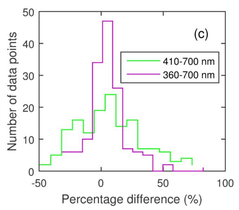


Fig.5(c). Error distributions of the estimated S_{dg} using the spectral R_{rs} with both UV and visible bands versus those from the R_{rs} with visible bands only.

Table 1. Error statistics of the estimated optical properties using 360-700 nm wavelengths. The values given in the parentheses refer to the error statistics for using the spectral R_{rs} between 410-700 nm.

Parameters	RMSE (nm^{-1})	δ	R^2	Slope of linear fit	Intercept of linear fit
$a_{ph}(440)$	0.00176	9.5%	0.92	0.996	0.00042
	(0.00184)	(12.8%)	(0.92)	(0.972)	(0.00057)
$a_{dg}(440)$	0.0029	19.9%	0.95	0.888	0.0016
	(0.0031)	(22.5%)	(0.94)	(0.881)	(0.0018)
$b_{bp}(440)$	0.00041	10.3%	0.97	0.987	0.00011
	(0.00036)	(8.2%)	(0.97)	(0.999)	(0.00007)
S_{dg}	0.002	11%	0.60	1.471	-0.006
	(0.004)	(22%)	(0.29)	(2.707)	(0.536)

- **Error propagations**

  Accurate estimation of S_{dg} is important for accurate assessment of the CDM spectral absorption $a_{dg}(\lambda)$, particularly, at UV wavebands.

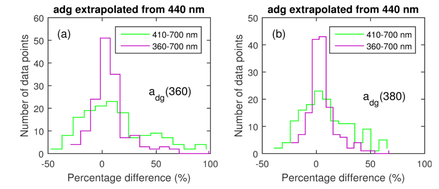


Fig.6 Comparison of the percentage errors due to the error propagation of spectral slopes estimated with and without UV wavelengths. (a) $a_{dg}(360)$ extrapolated from known $a_{dg}(440)$. (b) $a_{dg}(360)$ extrapolated from known $a_{dg}(440)$.

- **Dependence on the numbers of UV wavebands**

  Addition of even one UV waveband into the hyperspectral ocean color will improve the estimation of S_{dg}. The improvement can be greater if more than one UV wavebands are included.

Spectral domain (nm)	RMSE (nm^{-1})	δ	R^2	Slope of linear fit	Intercept of linear fit
360-700	0.002	11%	0.60	1.471	-0.006
360, 410-700	0.0025	14%	0.46	1.643	-0.009
380, 410-700	0.0027	16%	0.42	1.807	-0.011
410-700	0.004	22%	0.29	2.707	0.536

Table 2. Error statistics of the estimated spectrally constant slope S_{dg} using the R_{rs} at different wavelengths.

4. Concluding remarks

- ❑ The observation of the unique features in the hyperspectral remote sensing reflectance spectra (360-700nm) from various oceanic waters has inspired this study.
- ❑ Because the CDM absorption is much stronger than the phytoplankton absorption in the UV domain, the change of the CDM absorption with S_{dg} significantly alters the shapes of R_{rs} in the UV domain.
- ❑ The results suggest that the addition of UV wavebands to the ocean color greatly improve the retrievals of the spectral slopes, with a significant increase in the accuracy.
- ❑ The analyses also indicate that adding one UV waveband will still increase the accuracies of the S_{dg} retrievals, but the more the better.
- ❑ This study further emphasizes the necessity of using the UV wavebands for the total absorption decomposition into phytoplankton and CDM absorptions (Wei and Lee, 2015) and echoes the promotions of including UV wavebands in the next generation of satellite ocean color sensors, such as GeoCAPE and PACE.

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