Monitoring Water Quality of Inland Lakes by Remotely Sensed Observations

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Outline

Sect. 1 General introduction

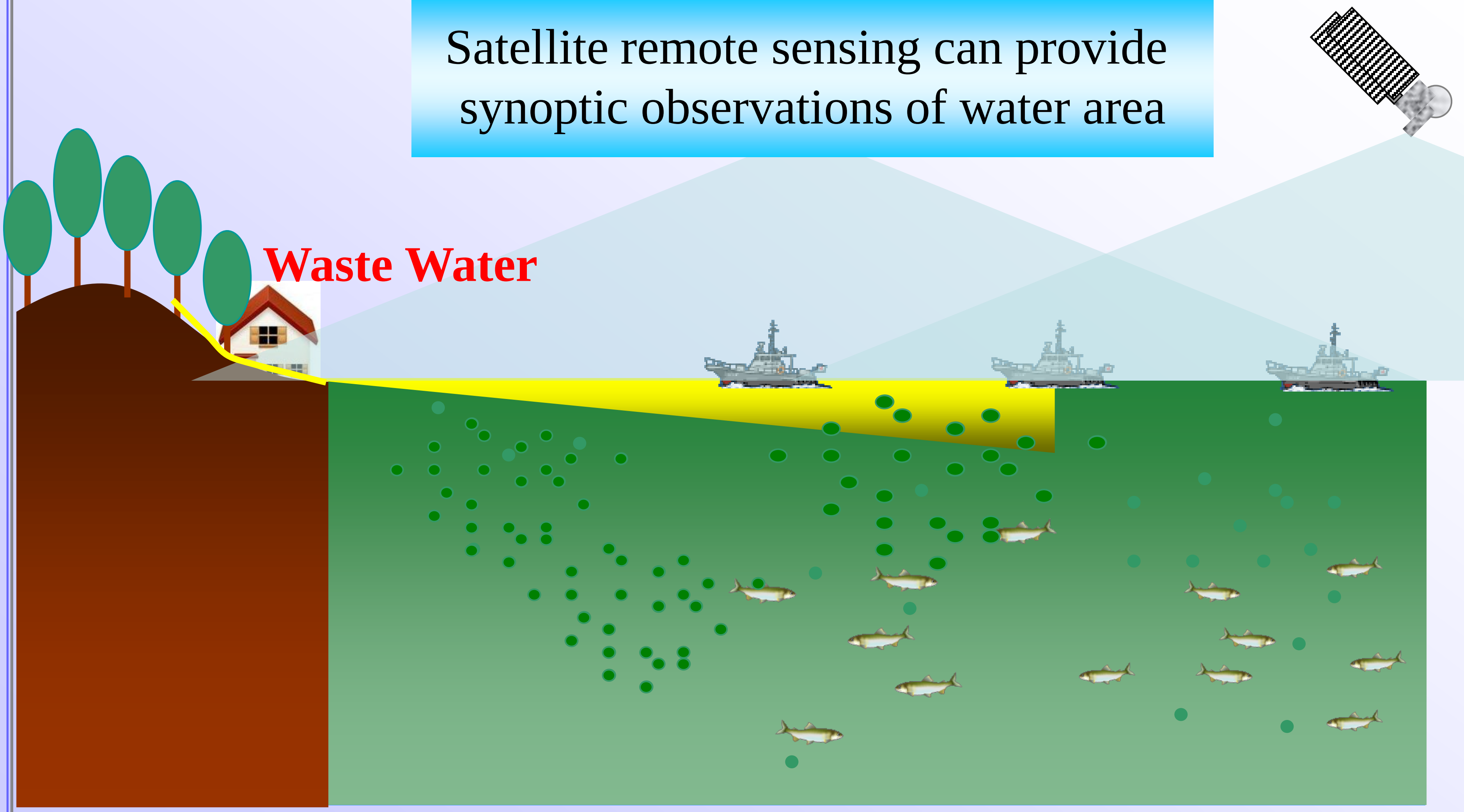
Sect.2 **Enhanced Three-band Index** for monitoring Chlorophyll-a

Sect.3 **SAMO-LUT algorithm** for monitoring water constituent concentrations

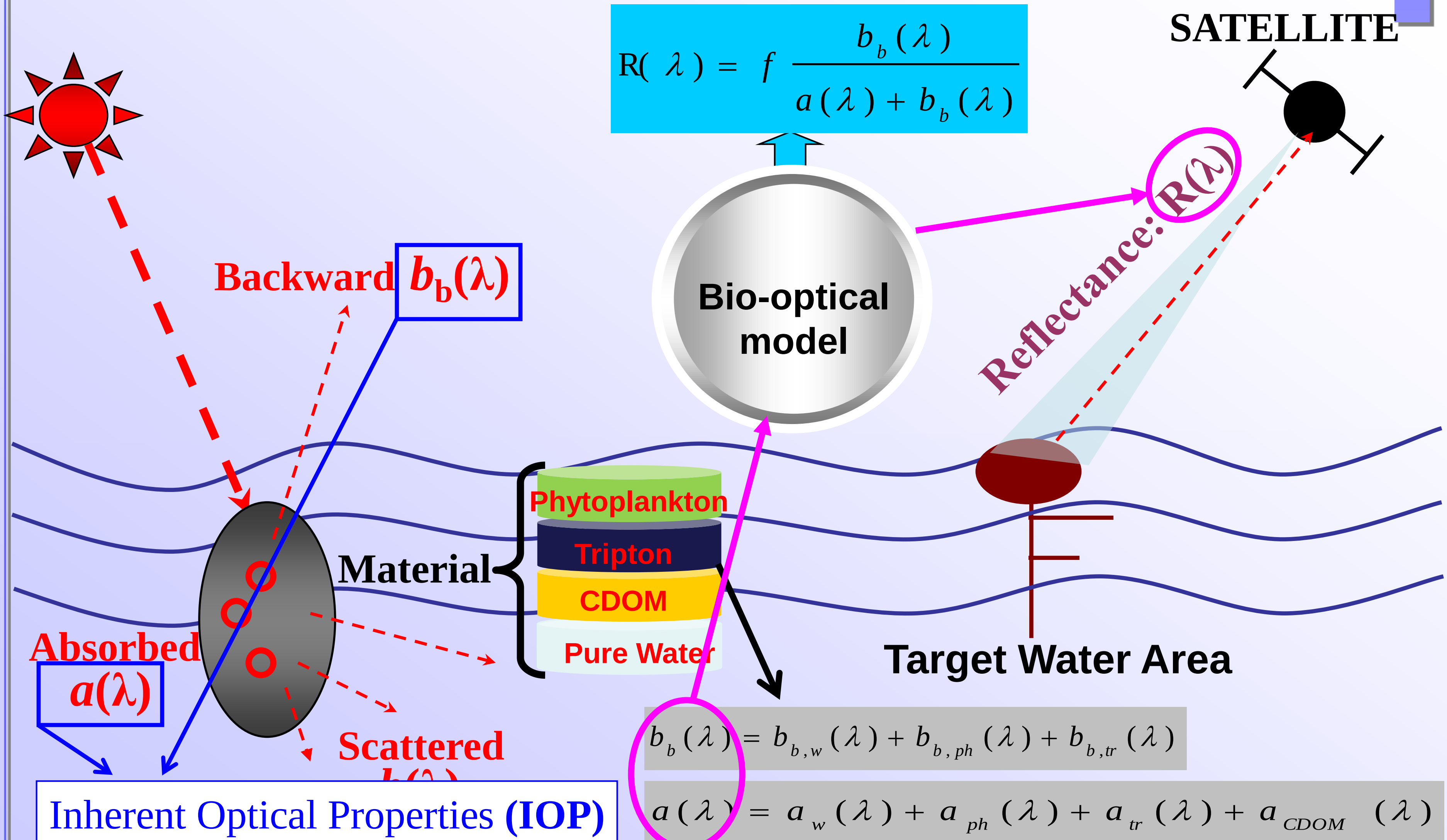
Sect. 4 General conclusions

Advantage of Satellite Remote Sensing

Satellite remote sensing can provide synoptic observations of water area



Physical Principle of Remote Sensing in Water Body



$$R(\lambda) = f\left[\frac{b_b(\lambda)}{a(\lambda) + b_b(\lambda)}\right]$$

$$b_b(\lambda) = b_{b,w}(\lambda) + b_{b,ph}(\lambda) + b_{b,tr}(\lambda)$$

$$a(\lambda) = a_w(\lambda) + a_{ph}(\lambda) + a_{tr}(\lambda) + a_{CDOM}(\lambda)$$

Specific Inherent Optical Properties (SIOP) = IOP/Concentration

Water Types: the Perspective of Remote Sensing

- Case I waters : waters are those dominated by phytoplankton (e.g. open oceans).

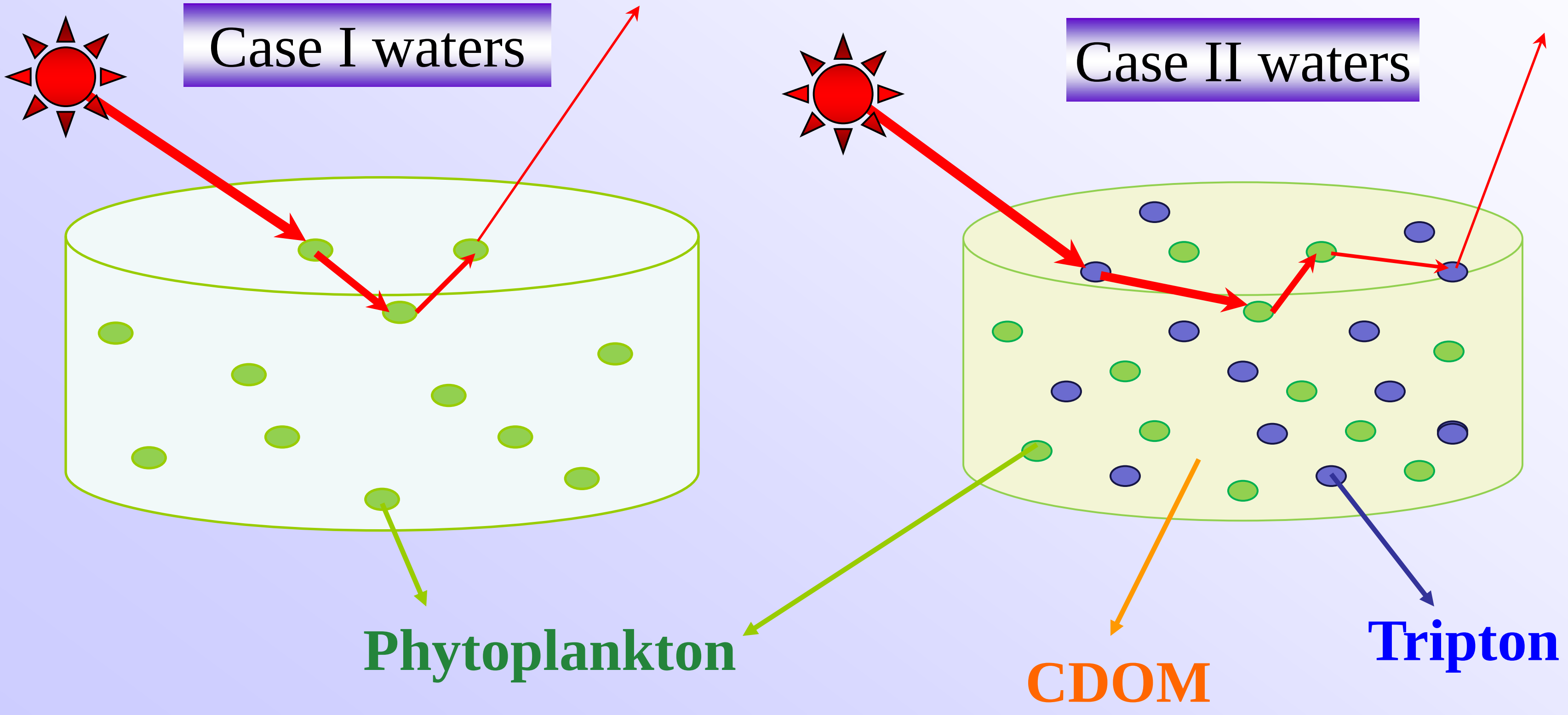
Chl-a can be satisfactorily estimated with satellite images (Gordon & Morel, 1983)

- Case II waters : waters are containing not only phytoplankton, but also non-phytoplankton suspended solids (i.e., tripton) and colored dissolved organic matters (CDOM) (e.g. coastal and inland waters).

Still challenging

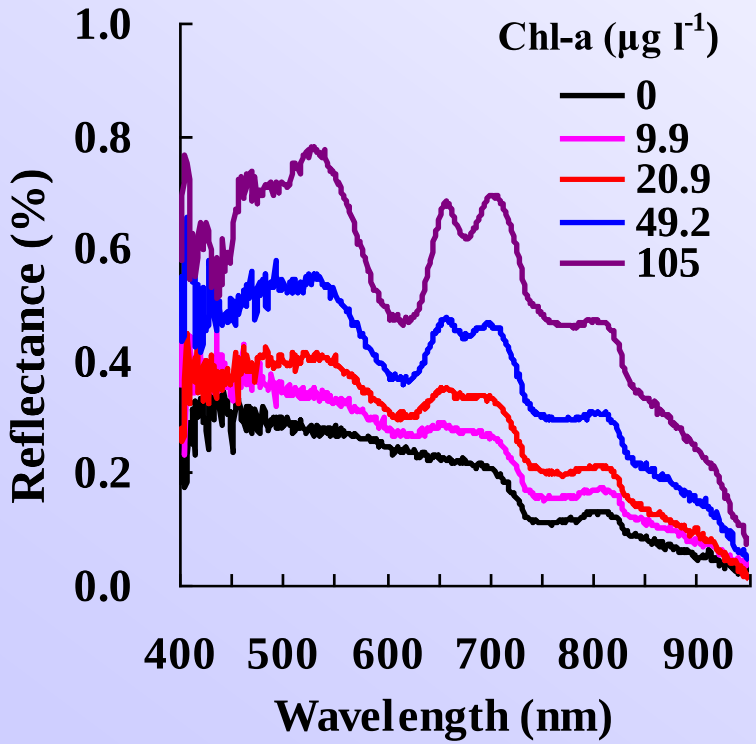
Difficulty for Monitoring Case II Waters

Interactions between Different Components

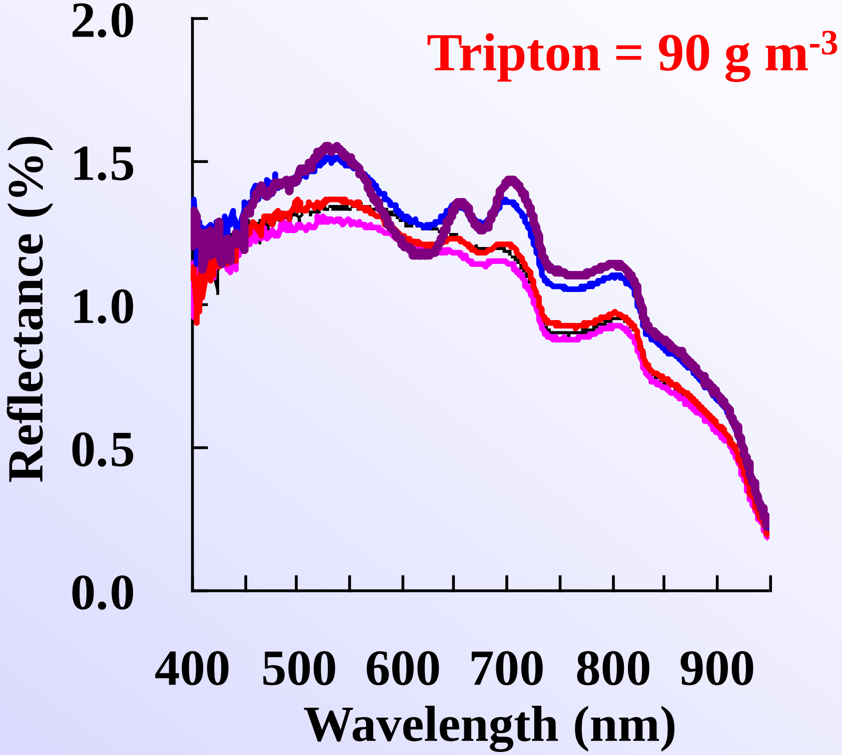


Reflectance spectra for case I and II waters

Case I waters



Case II waters



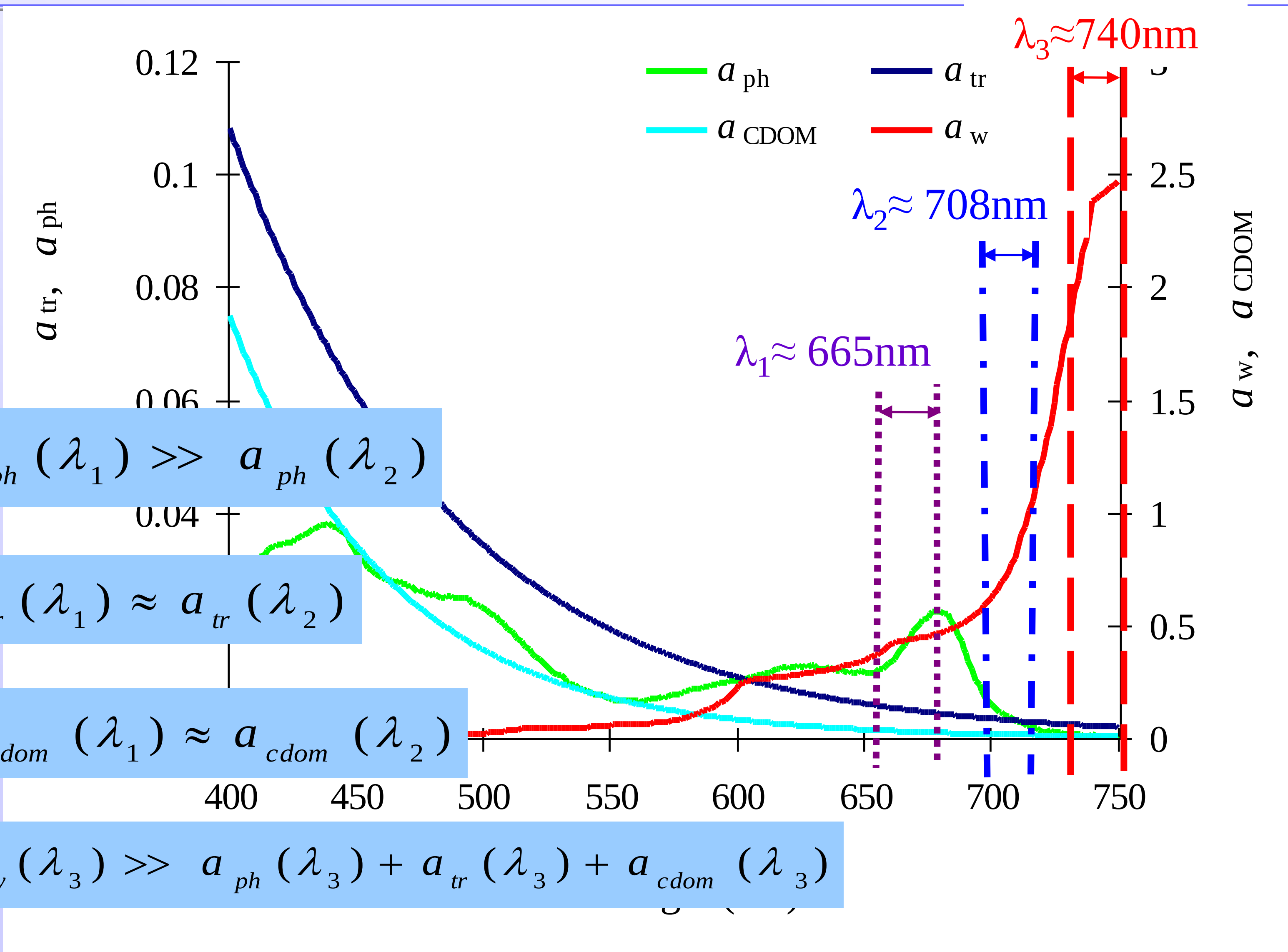
Review of Previous Studies for Remote Sensing in Case II Waters

- A number of methods have been proposed, e.g., Matrix Inversion Method (Hoogenboom *et al*., 1998), Band-ratio index (Gons, 1999; Ammenberg *et al*., 2002), Three-band index (Gitelson et al., 2008), and so on.

- The basic idea for all of the methods is to isolate the interactions between different components.

- Among these methods, the 3-band index significantly outperformed other indices (Gitelson *et al*., 2008).

Principle of the 3-band index: Absorption



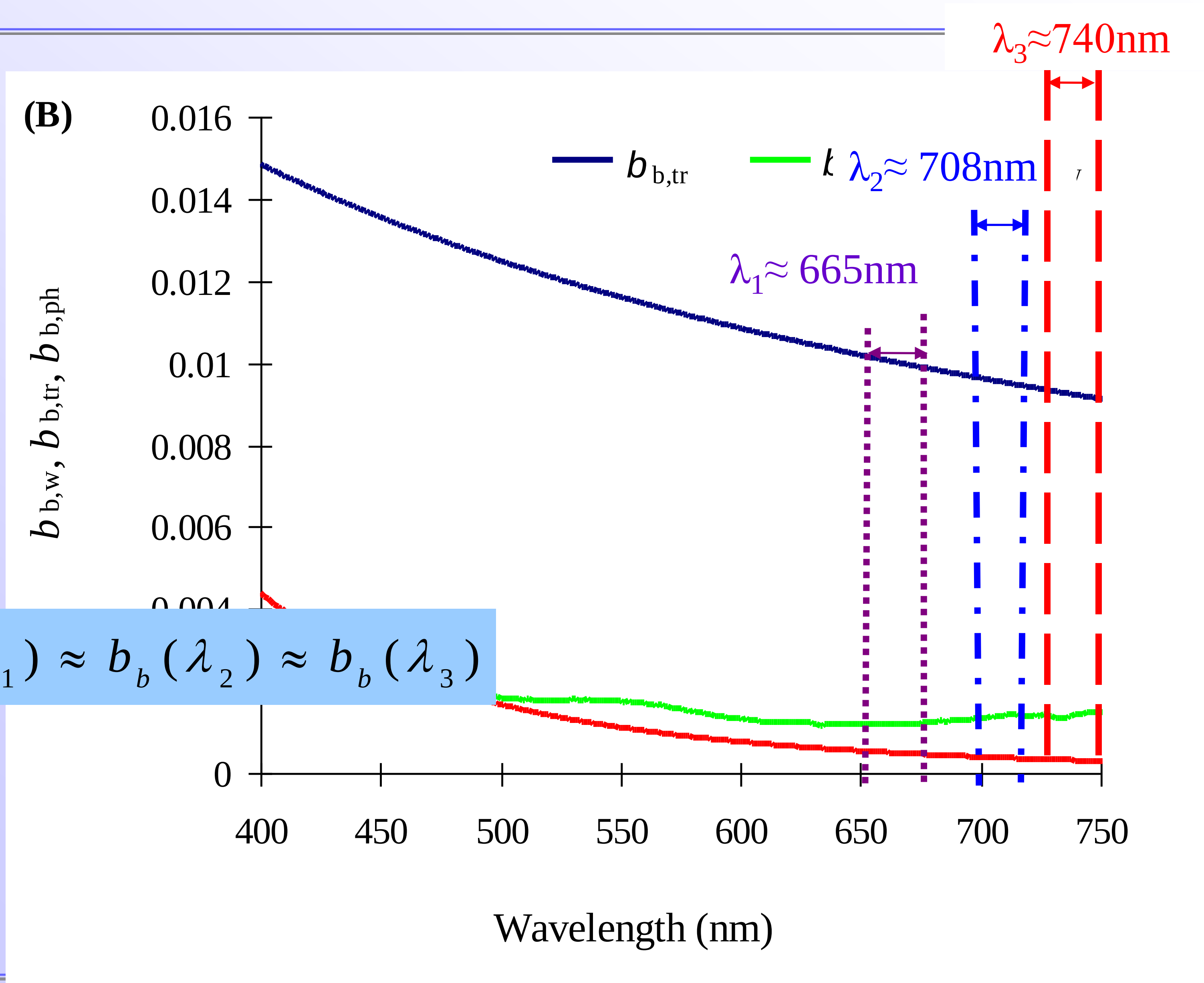
$$a_{ph}(\lambda_1) >> a_{ph}(\lambda_2)$$

$$a_{tr}(\lambda_1) \approx a_{tr}(\lambda_2)$$

$$a_{cdom}(\lambda_1) \approx a_{cdom}(\lambda_2)$$

$$a_w(\lambda_3) >> a_{ph}(\lambda_3) + a_{tr}(\lambda_3) + a_{cdom}(\lambda_3)$$

Principle of the 3-band index: Backscattering



$$b_b(\lambda_1) \approx b_b(\lambda_2) \approx b_b(\lambda_3)$$

Principle of the 3-band index: Reflectance

$$(\frac{1}{R_1} - \frac{1}{R_2}) \times R_3$$

$$= \frac{1}{f}(\frac{a_1 + b_{b,1}}{b_{b,1}} - \frac{a_2 + b_{b,2}}{b_{b,2}}) \times f\frac{b_{b,3}}{a_3 + b_{b,3}}$$

$$b_{b,1} = b_{b,2}$$

$$\approx \frac{a_1 + b_{b,1} - (a_2 + b_{b,2})}{b_{b,1}} \times \frac{b_{b,3}}{a_3 + b_{b,3}}$$

$$\approx \frac{a_1 - a_2}{a_3 + b_{b,3}}$$

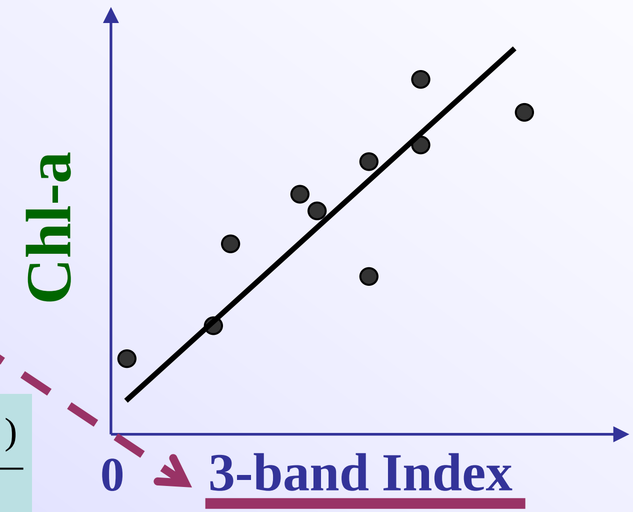
$\propto$ Chl − a

$$= \frac{(a_{ph,1} + a_{tr,1} + a_{CDOM,1} + a_{w,1}) - (a_{ph,2} + a_{tr,2} + a_{CDOM,2} + a_{w,2})}{a_{w,3} + a_{ph,3} + a_{tr,3} + a_{CDOM,3} + b_{b,3}}$$

$$\approx \frac{a_{ph,1}}{a_{w,3}} + \frac{a_{w,1} - a_{w,2}}{a_{w,3}}$$

Constants

$$\text{Chl} - \text{a} = m \cdot (\frac{1}{R_1} - \frac{1}{R_2}) \times R_3 + n$$



Problem of the 3-band index

For waters with high turbidity (e.g. some Asian Lakes), the assumption

$$a_{water}(\lambda_3) \gg a_{ph}(\lambda_3) + a_{tripton}(\lambda_3) + a_{CDOM}(\lambda_3)$$

is not reasonable anymore (Le *et al*., 2009).

In these cases, the 3-band index becomes:

$$[1/R_{rs}(\lambda_1) - 1/R_{rs}(\lambda_2)] \times R_{rs}(\lambda_3) \approx \frac{a_{ph}(\lambda_1) + a_w(\lambda_1) - a_w(\lambda_2)}{a_w(\lambda_3) + a_{ph}(\lambda_3) + a_{tr}(\lambda_3) + a_{CDOM}(\lambda_3)}$$

$\propto$ Chl – a

Denominator includes the absorption not only phytoplankton, but also tripton and CDOM

The existing methods still cannot provide satisfactory estimations for turbid case II waters.

Main objectives of my research

1. To develop more effective methods to isolate the interactions between water components

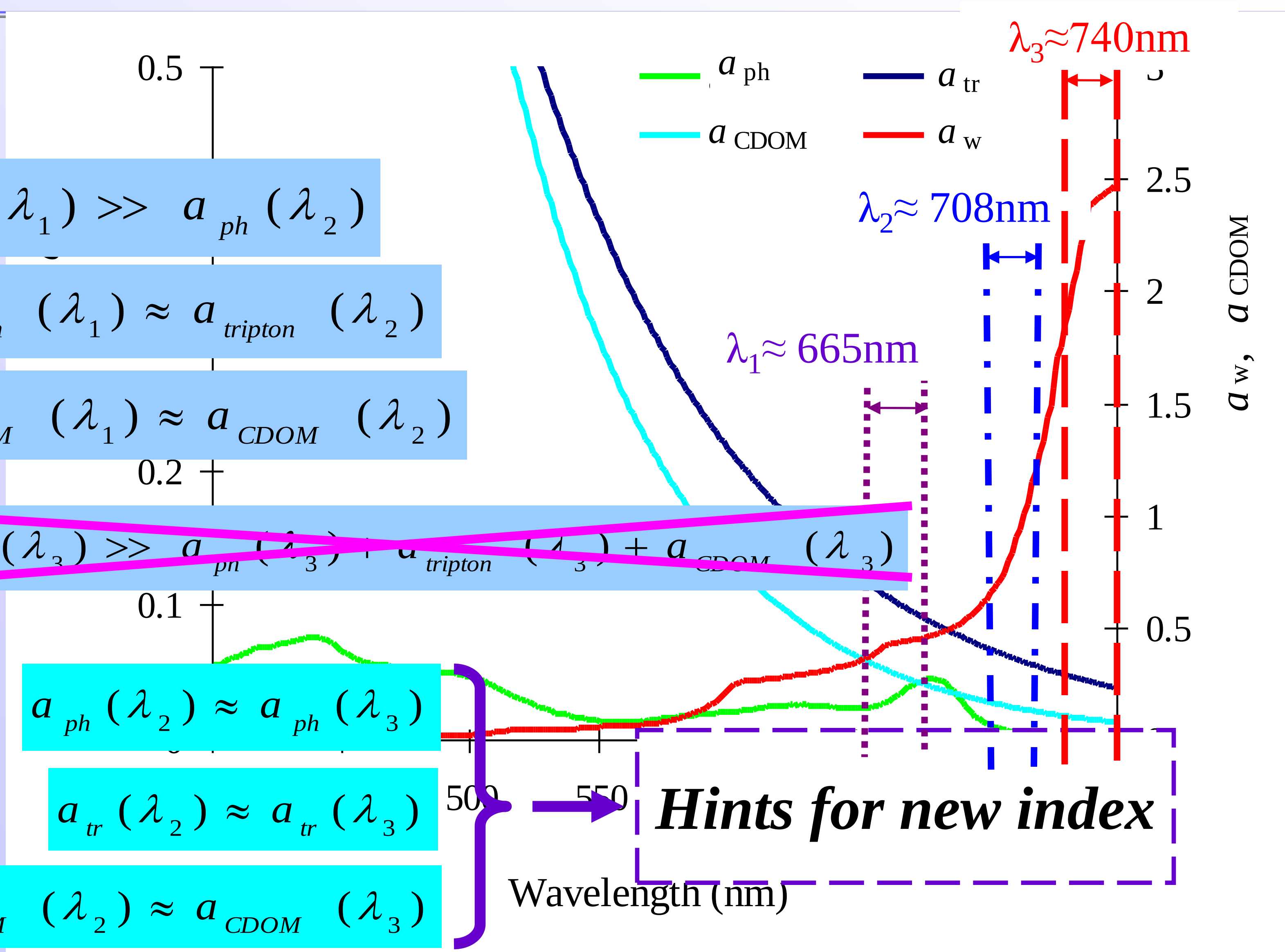
2. To validate their performances using simulation, *in situ* and satellite datasets

Section 2

An Enhanced 3-band Index for estimating Chl-a in turbid Case II waters

Absorption properties for turbid water case

(e.g. TSS=20 g m^{-3})



$$a_{ph}(\lambda_1) >> a_{ph}(\lambda_2)$$

$$a_{tripton}(\lambda_1) \approx a_{tripton}(\lambda_2)$$

$$a_{CDOM}(\lambda_1) \approx a_{CDOM}(\lambda_2)$$

~~$a_{water}(\lambda_3) >> a_{ph}(\lambda_3) + a_{tripton}(\lambda_3) + a_{CDOM}(\lambda_3)$~~

$$a_{ph}(\lambda_2) \approx a_{ph}(\lambda_3)$$

$$a_{tr}(\lambda_2) \approx a_{tr}(\lambda_3)$$

$$a_{CDOM}(\lambda_2) \approx a_{CDOM}(\lambda_3)$$

→ ***Hints for new index***

Development of the Enhanced 3-band Index

$$[1/R_{rs}(\lambda_1) - 1/R_{rs}(\lambda_2)] \Big/ [1/R_{rs}(\lambda_3) - 1/R_{rs}(\lambda_2)]$$

$$= \frac{\frac{1}{f}\left(\frac{a_1 + b_{b,1}}{b_{b,1}} - \frac{a_2 + b_{b,2}}{b_{b,2}}\right)}{\frac{1}{f}\left(\frac{a_3 + b_{b,3}}{b_{b,3}} - \frac{a_2 + b_{b,2}}{b_{b,2}}\right)}$$

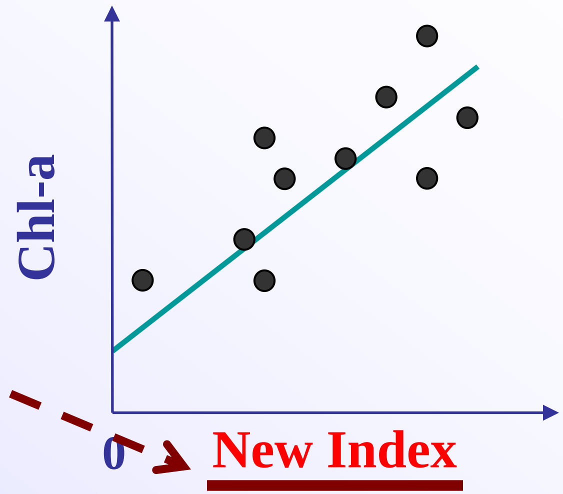
$$\approx \frac{a_1 - a_2}{a_3 - a_2}$$

$$= \frac{(a_{ph,1} + a_{tr,1} + a_{CDOM,1} + a_{w,1}) - (a_{ph,2} + a_{tr,2} + a_{CDOM,2} + a_{w,2})}{(a_{ph,3} + a_{tr,3} + a_{CDOM,3} + a_{w,3}) - (a_{ph,2} + a_{tr,2} + a_{CDOM,2} + a_{w,2})}$$

$$\approx [a_{ph}(\lambda_1) + a_w(\lambda_1) - a_w(\lambda_2)] \Big/ [a_w(\lambda_3) - a_w(\lambda_2)]$$

$\propto [\mathrm{Chl} - \mathrm{a}]$

Constants



Chl-a = *l* × New Index + *m*

Study Areas

Lake Kasumigaura,
Japa

Location: Ibara

Lake Dianchi,
China

Location: Yunnan Province, China
Area: 300 ㎞²
Average depth：6 m
Case II water:
- **mixture of phytoplankton, tripton, and CDOM**
- **dominant species cyanobacteria**

Field survey: 4 times (Oct. 23, 2007; Jul. 15, 2008; Mar. 12, 2009; Jul.-Aug., 2009)
Total 53 sites

Data Collections

Phytoplankton (Chl-a)

Samples taken to lab;

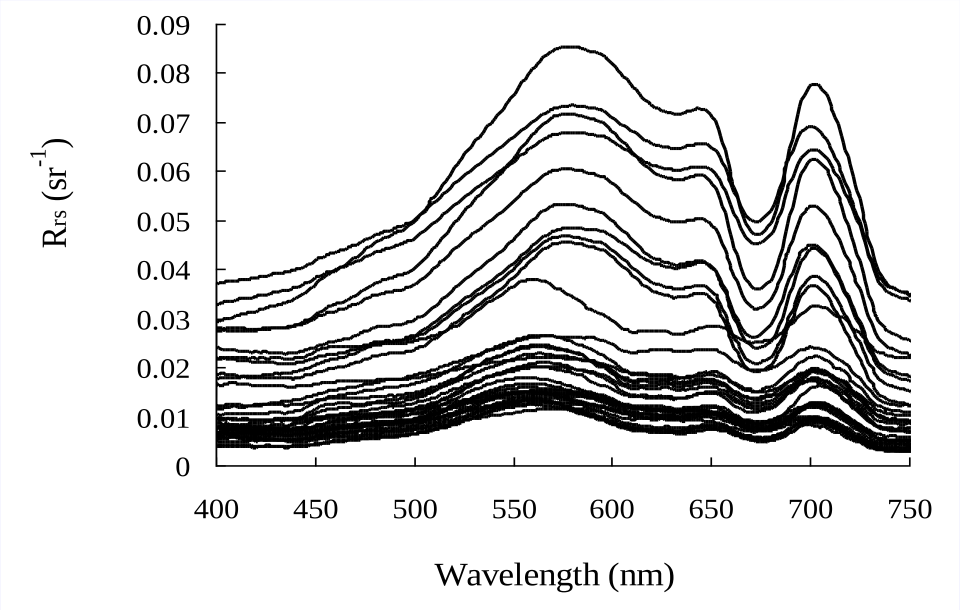
SCOR-UNESCO equations.

Remote sensing reflectance

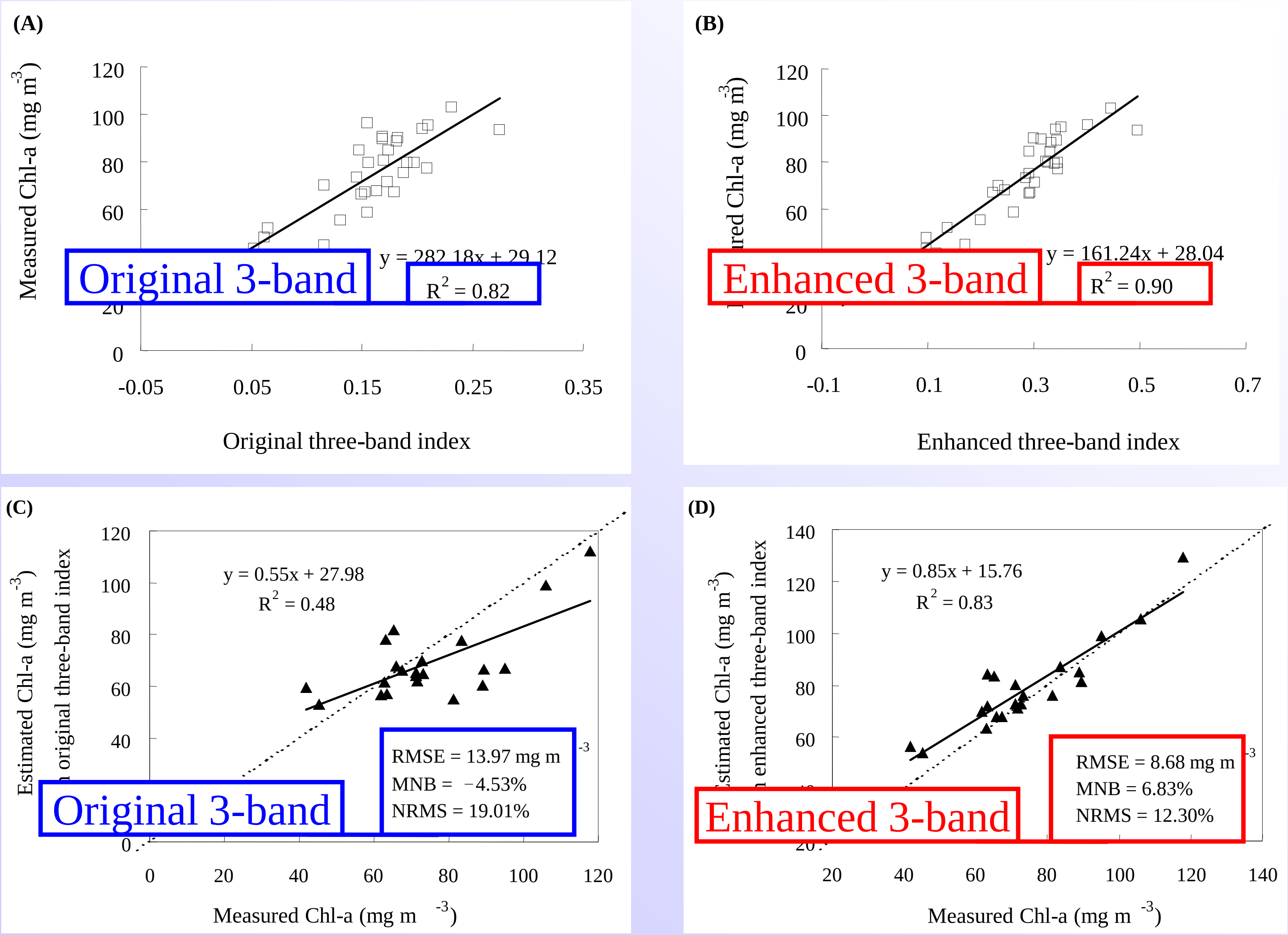
Water-leaving radiance;

Downward irradiance;

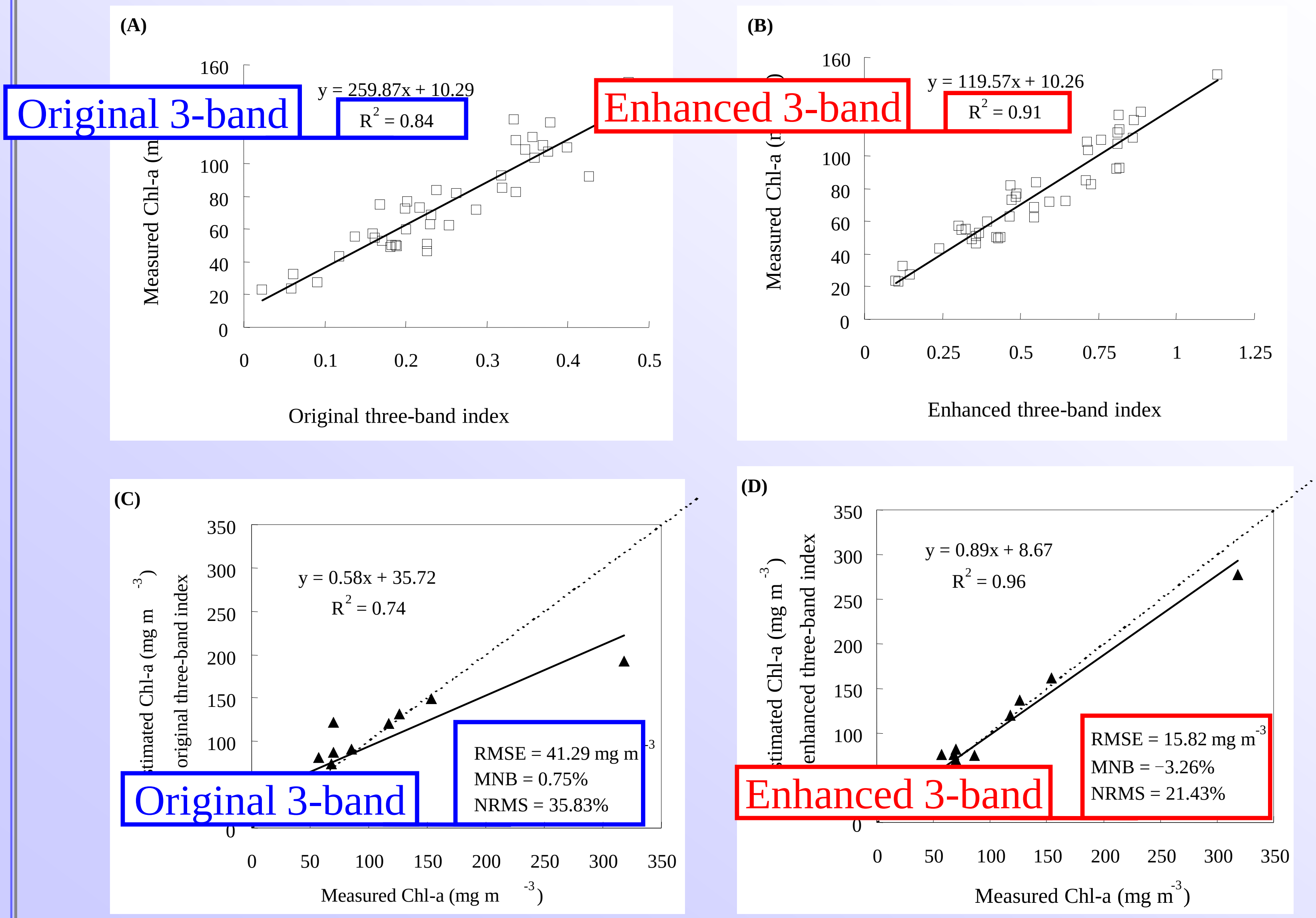
Downward radiance of skylight.



Results for **Lake** Kasumigaura, Japan



Results for Lake Dianchi, China



Section 3

Estimation of water constituent concentrations in case II waters by semi-analytical model-optimizing and look-up-tables (SAMO-LUT)

***Objective*:**

To provide information of not only Chl-a, but also tripton and CDOM.

Selection of Three Previous Semi-analytical Models

- Chl-a estimation model (3-band index):

$$Chla = p \times [R_{rs}^{-1}(B_7) - R_{rs}^{-1}(B_9)] \times R_{rs}(B_{10}) + q$$

(Gitelson *et al.*, 2008)

- Tripton estimation model:

$$Tr = m \times R_{rs}(B_{10}) + n$$

(Ammenberg *et al.*, 2002)

- CDOM estimation model:

$$a_{CDOM}(440) = a \times [R_{rs}(B_7) / R_{rs}(B_5)] + b$$

(Ammenberg *et al.*, 2002)

B_5, B_7, B_9, and B_{10} denote MERIS bands 5 (555-565 nm), 7 (660-670 nm), 9 (703-713 nm), and 10 (750-757 nm), respectively

Simulation test for re-analyzing previous models

- Remote-sensing reflectance generated from:

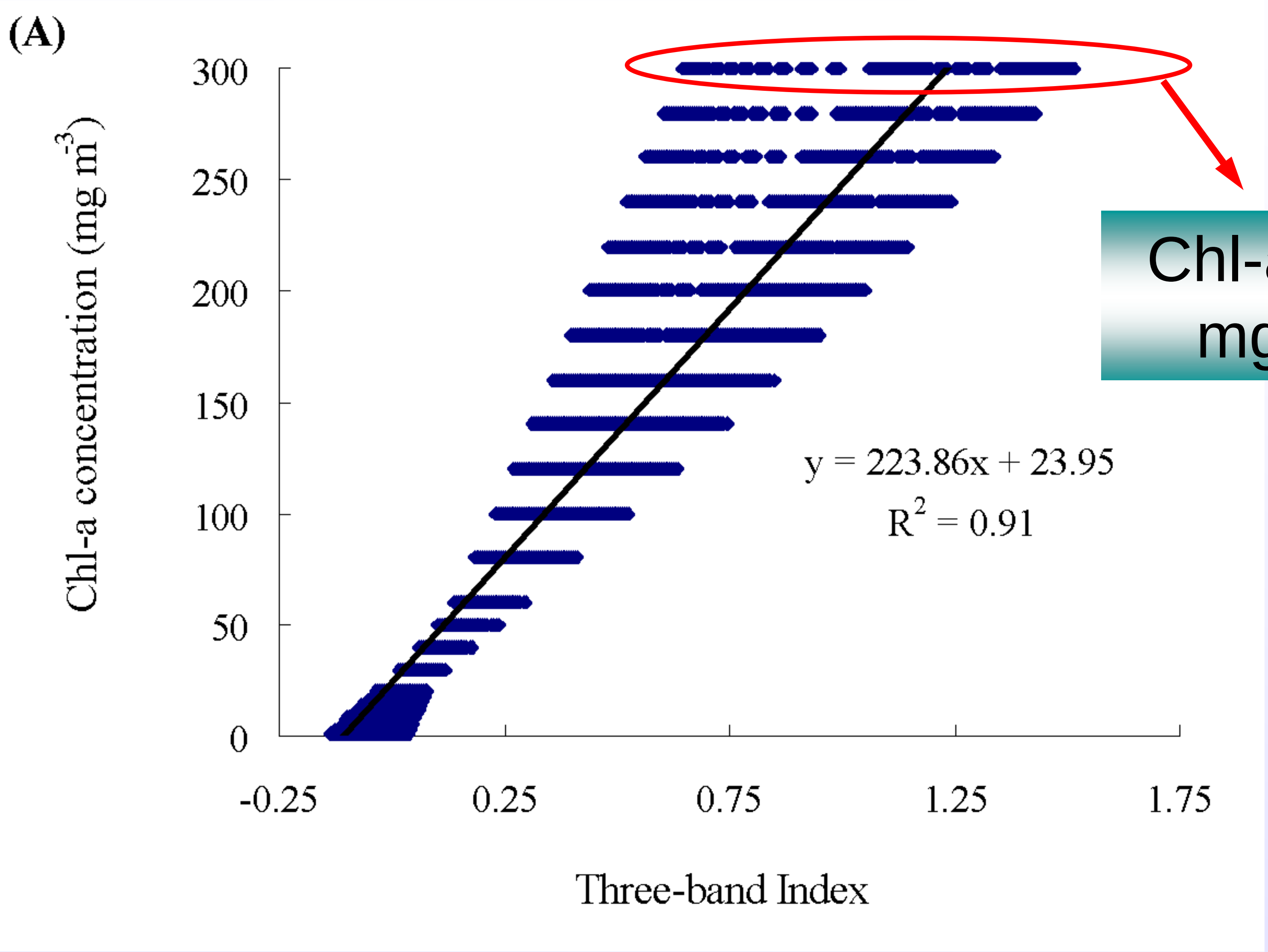
$$R_{rs}(\lambda) = f \frac{b_b(\lambda)}{a(\lambda) + b_b(\lambda)}$$

$$a = [Chl-a]a^*_{ph} + [Tr]a^*_{tr} + [CDOM]a^*_{CDOM} + a_w$$

$$b_b = [Chl-a]b^*_{b,ph} + [Tr]b^*_{b,tr} + b_{b,w}$$

- [Chl-a] ranges: 1-300 mg m^{-3};
- [Tr] ranges: 1-250 g m^{-3};
- [CDOM] ranges: 0.1-10 m^{-1}.
- In total, 19,964 samples for regression analysis

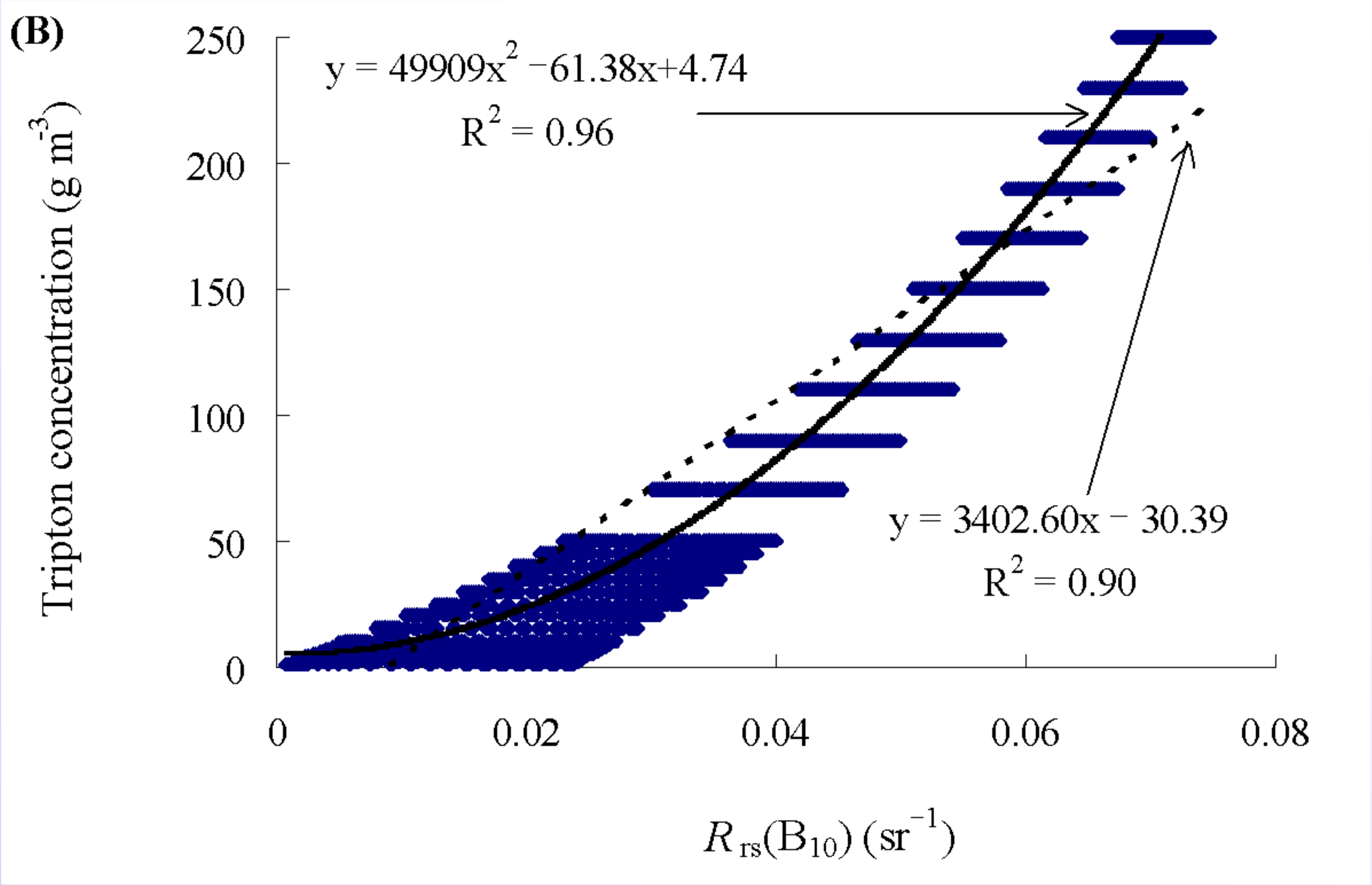
Problem for previous model
(Chl-a vs. 3-band index)



Chl-a=300 mg m^{-3}

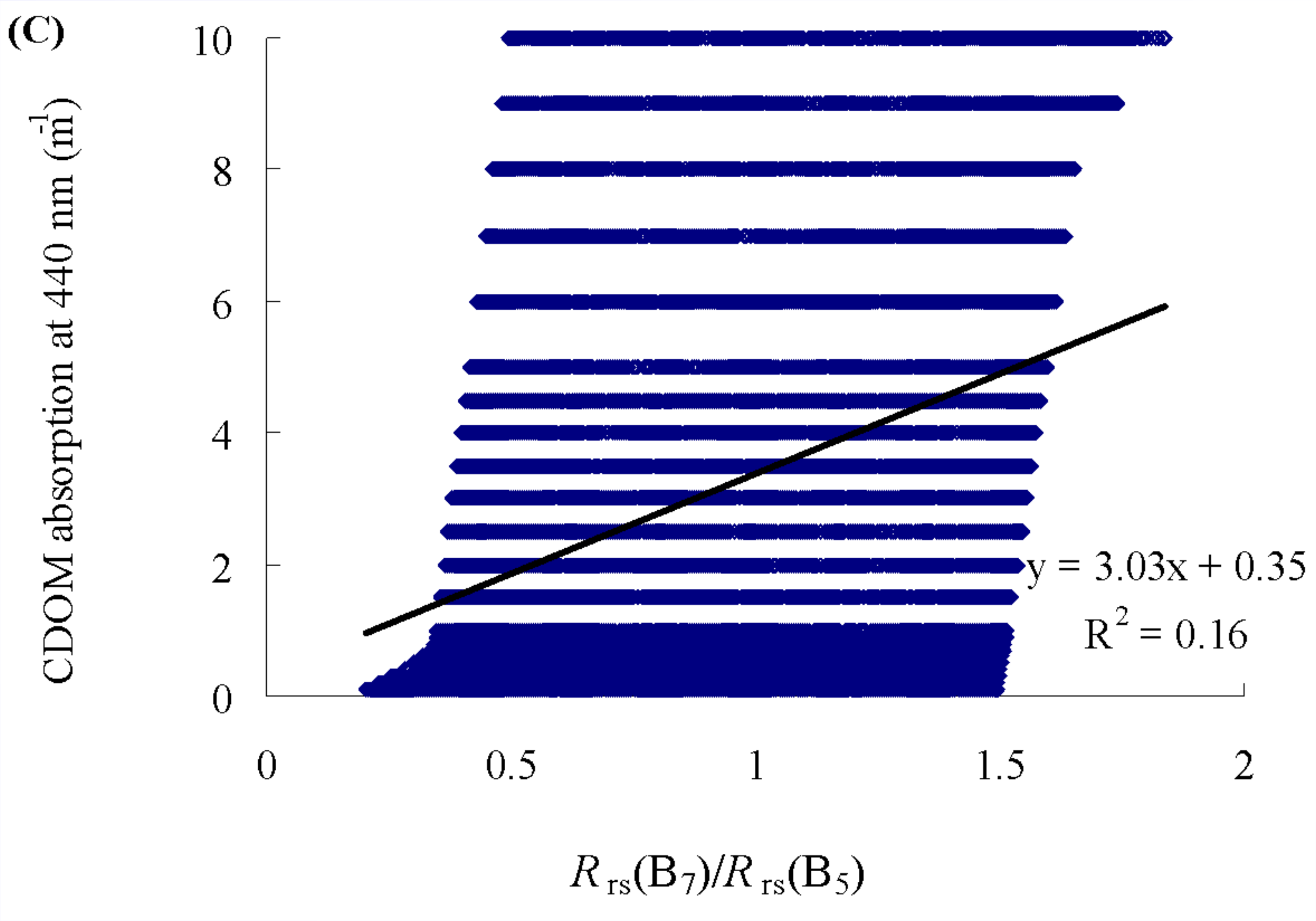
Problem for previous model

(Tripton vs. $R_{rs}(B_{10})$)



Problem for previous model

(CDOM Vs. $R_{rs}(b_7)/ R_{rs}(b_5)$)



Development of the new algorithm

Semi-**A**nalytical **M**odel-**O**ptimizing and **L**ook-**U**p **T**able (**SAMO-LUT**)

- Basic idea of this new method is an imaginary case II water, in which only one component changes while the other two are controlled as constants.

- E.g. Tr and CDOM are constants; only Chl-a is changing :

$$a = [Chl-a]a^{*}_{ph} + [Tr]a^{*}_{tr} + [CDOM]a^{*}_{CDOM} + a_{w}$$

$$b_{b} = [Chl-a]b^{*}_{b,ph} + [Tr]b^{*}_{b,tr} + b_{b,w}$$

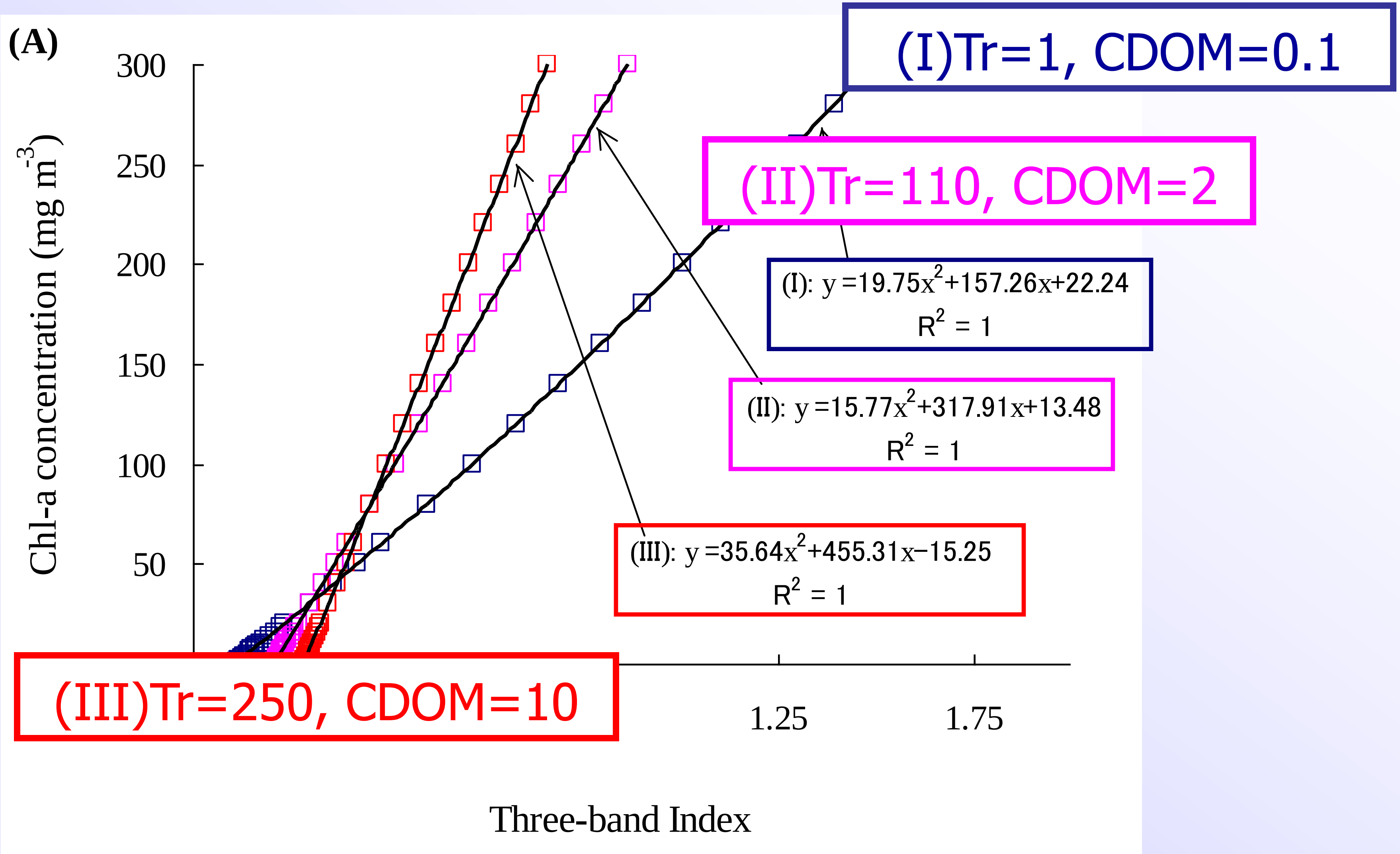
$$R_{rs}(\lambda) = f\frac{b_{b}(\lambda)}{a(\lambda) + b_{b}(\lambda)}$$

Constants

R_{rs} is changing only with Chl-a. → **Possibility for improving three-band index**

Example of tripton and CDOM controlled as constants

(e.g. Chl-a vs. 3-band index)



Construction of Look-up Tables (LUT) using simulation data

- The coefficients of Chl-a model for <u>each combination of Tripton and CDOM</u> are stored in the LUT.

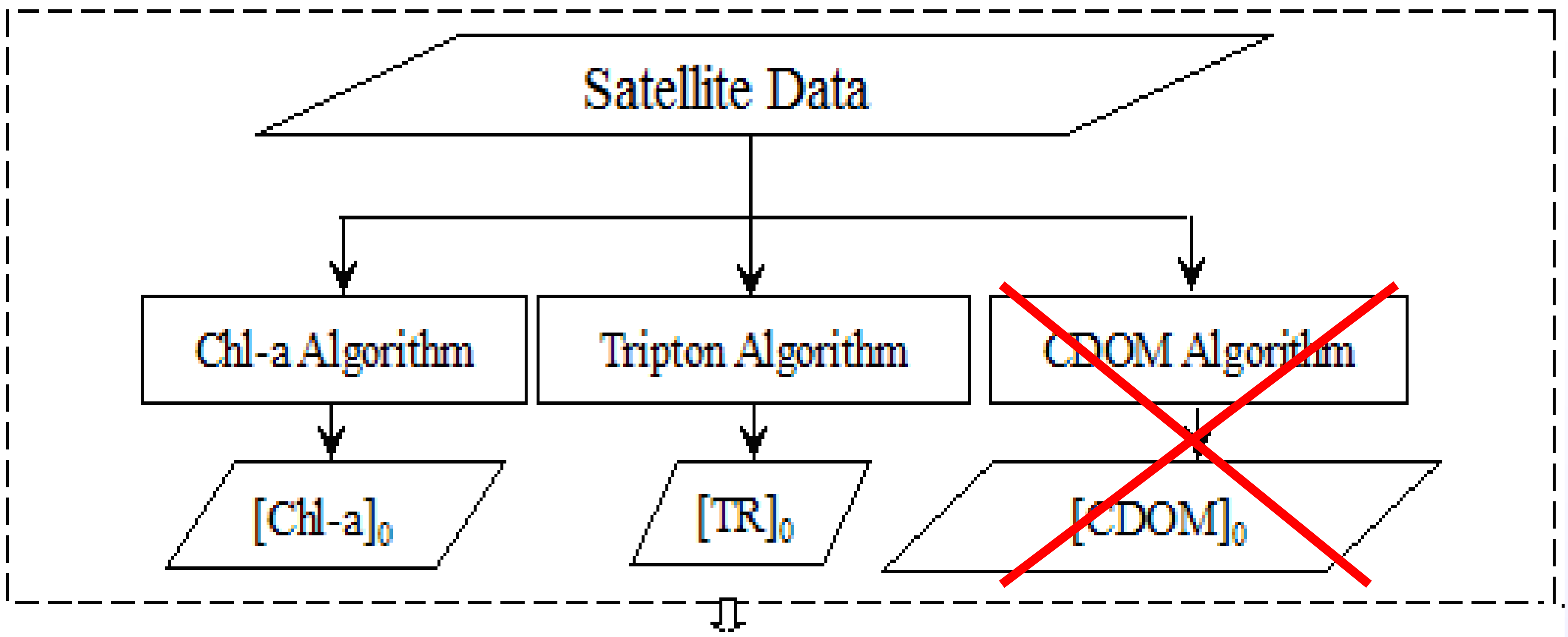
Tripton (g m^{-3})

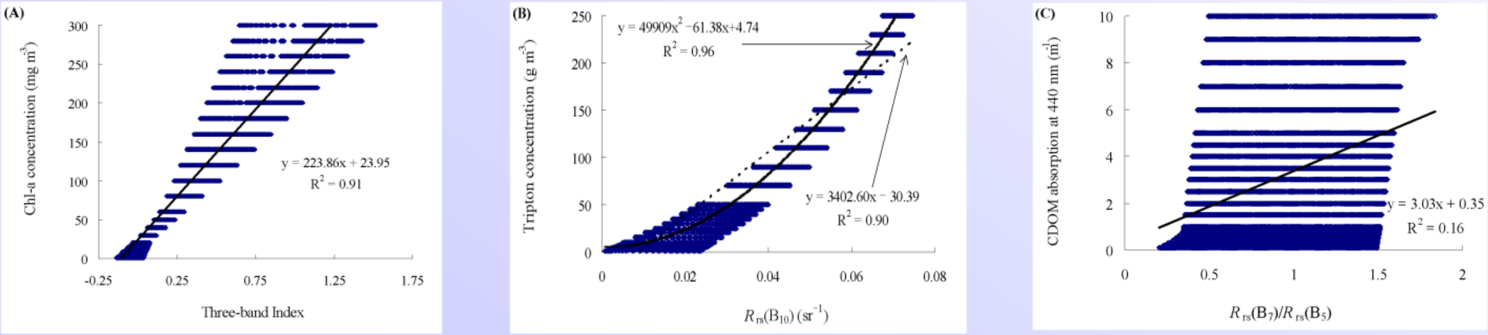
CDOM (m^{-1})	1	2	…	…	249	250
0.1	$(p_{1,1}; q_{1,1}; r_{1,1})$	$(p_{1,2}; q_{1,2}; r_{1,2})$	…	…	$(p_{1,249}; q_{1,249}; r_{1,249})$	$(p_{1,250}; q_{1,250}; r_{1,250})$
0.2	$(p_{2,1}; q_{2,1}; r_{2,1})$	$(p_{2,2}; q_{2,2}; r_{2,2})$	…	…	$(p_{2,249}; q_{2,249}; r_{2,249})$	$(p_{2,250}; q_{2,250}; r_{2,250})$
0.3	$(p_{3,1}; q_{3,1}; r_{3,1})$	$(p_{3,2}; q_{3,2}; r_{3,2})$	…	…	$(p_{3,249}; q_{3,249}; r_{3,249})$	$(p_{3,250}; q_{3,250}; r_{3,250})$
…	…	…	…	…	…	…
…	…	…	…	…	…	…
9.9	$(p_{99,1}; q_{99,1}; r_{99,1})$	$(p_{99,2}; q_{99,2}; r_{99,2})$	…	…	$(p_{99,249}; q_{99,249}; r_{99,249})$	$(p_{99,250}; q_{99,250}; r_{99,250})$
10	$(p_{100,1}; q_{100,1}; r_{100,1})$	$(p_{100,2}; q_{100,2}; r_{100,2})$	…	…	$(p_{100,249}; q_{100,249}; r_{100,249})$	$(p_{100,250}; q_{100,250}; r_{100,250})$

The practical problem is **<u>how to find the optimal models</u>** for a given pixel?

Iteration strategy in the SAMO-LUT method

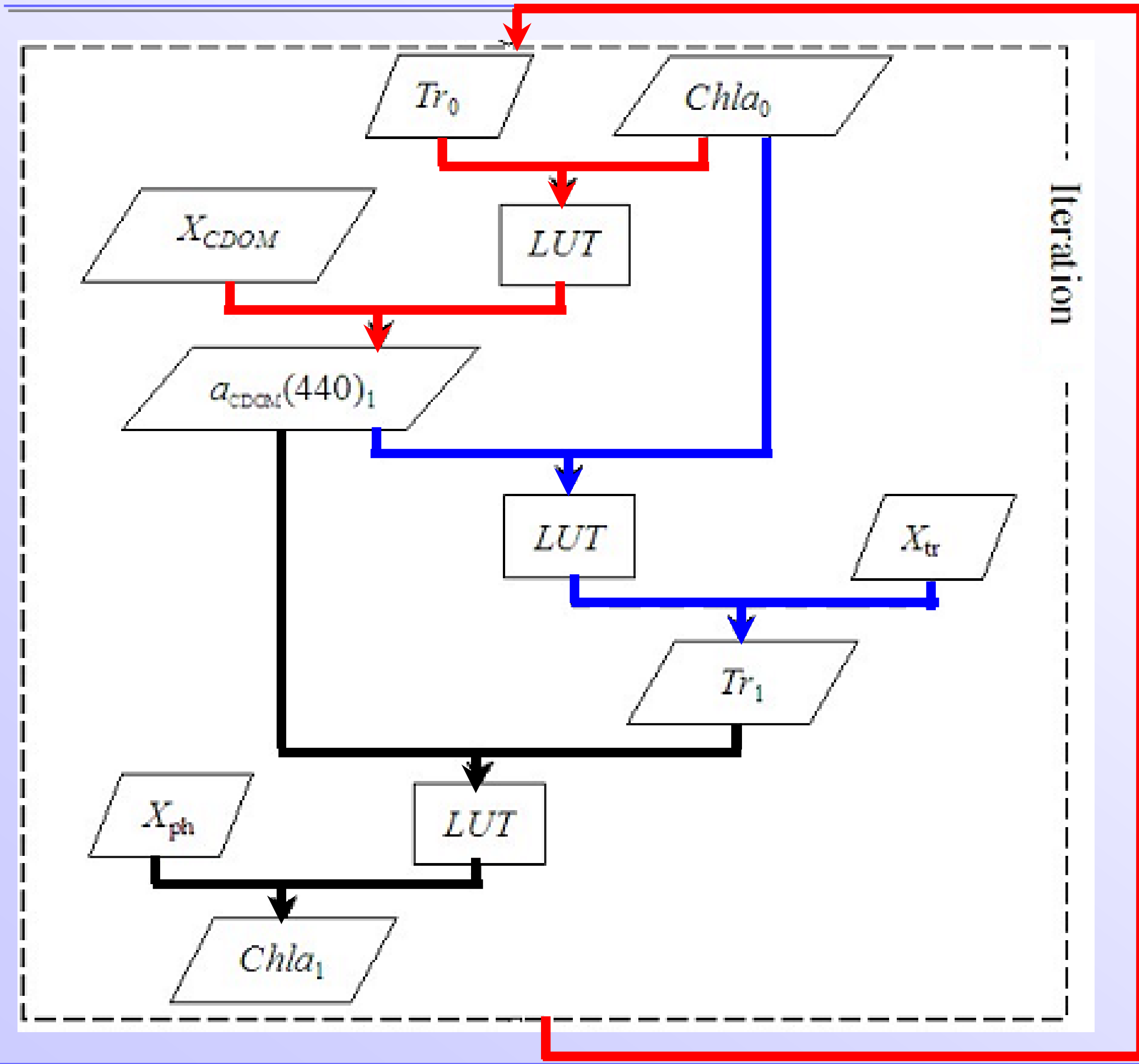
(Step 1: getting initial values)





Iteration strategy in the SAMO-LUT method

(Step 2: optimizing estimation model)

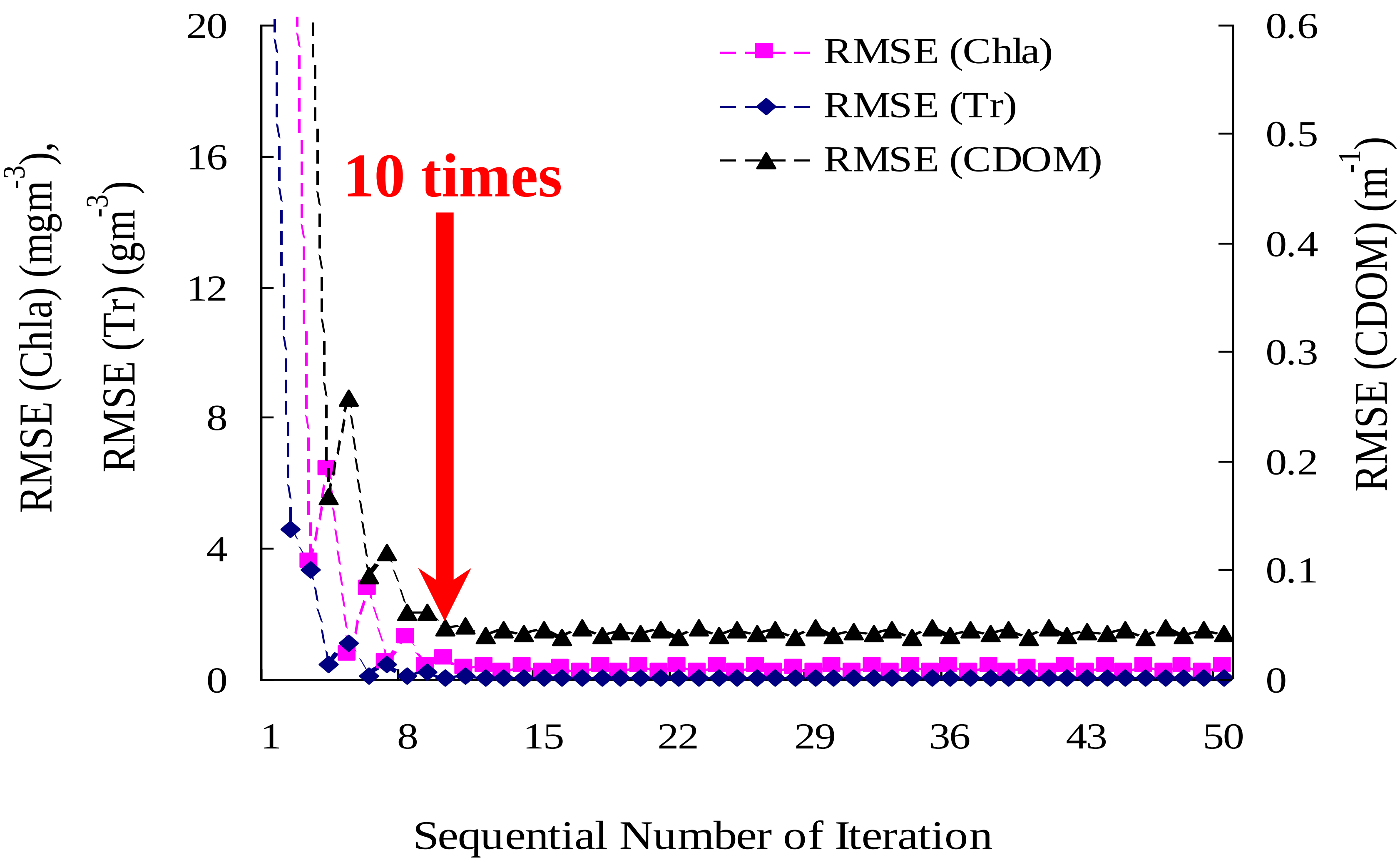


Repeat !

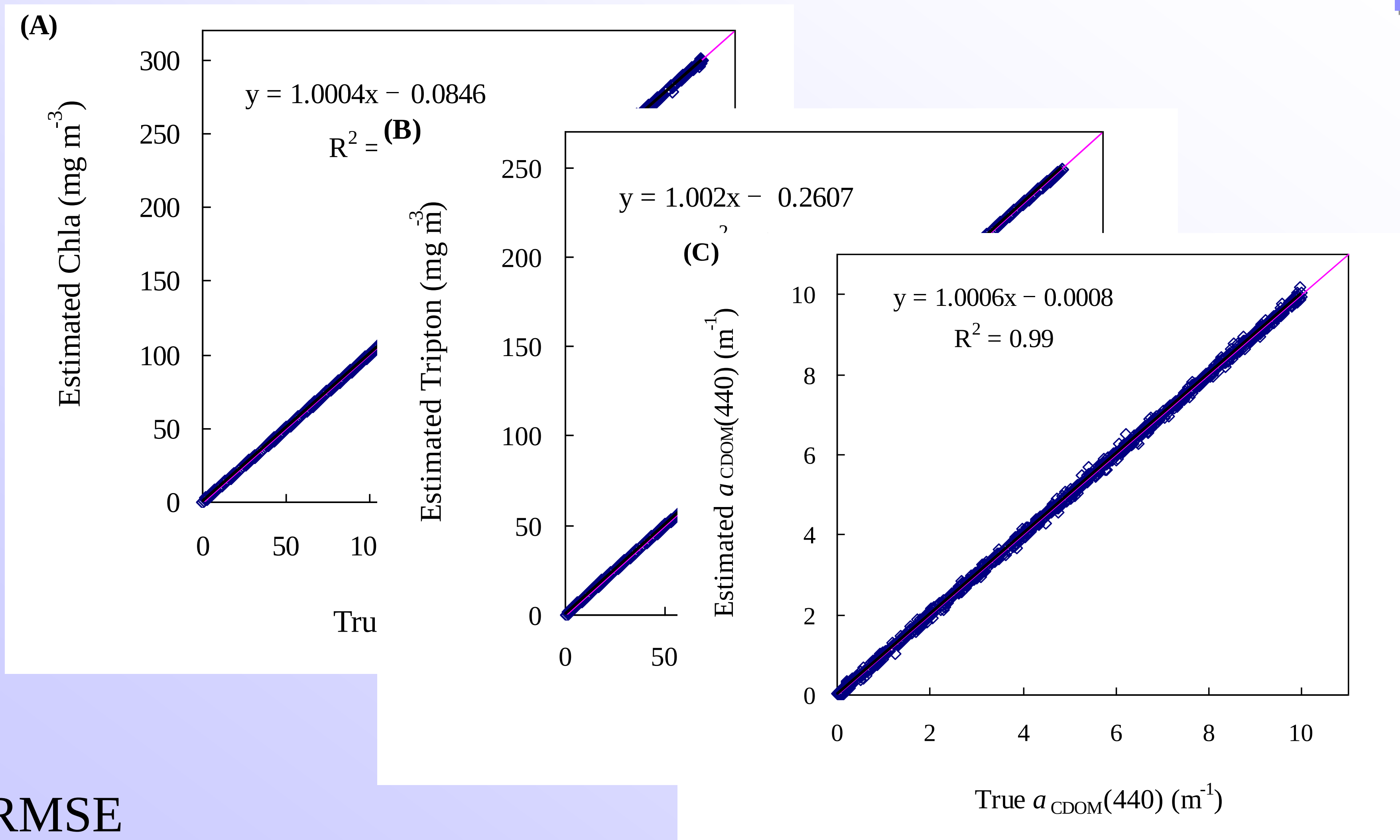
$Chla_0 = Chla_1$

$Tr_0 = Tr_1$

Ending the iteration by difference between the current and last iterations

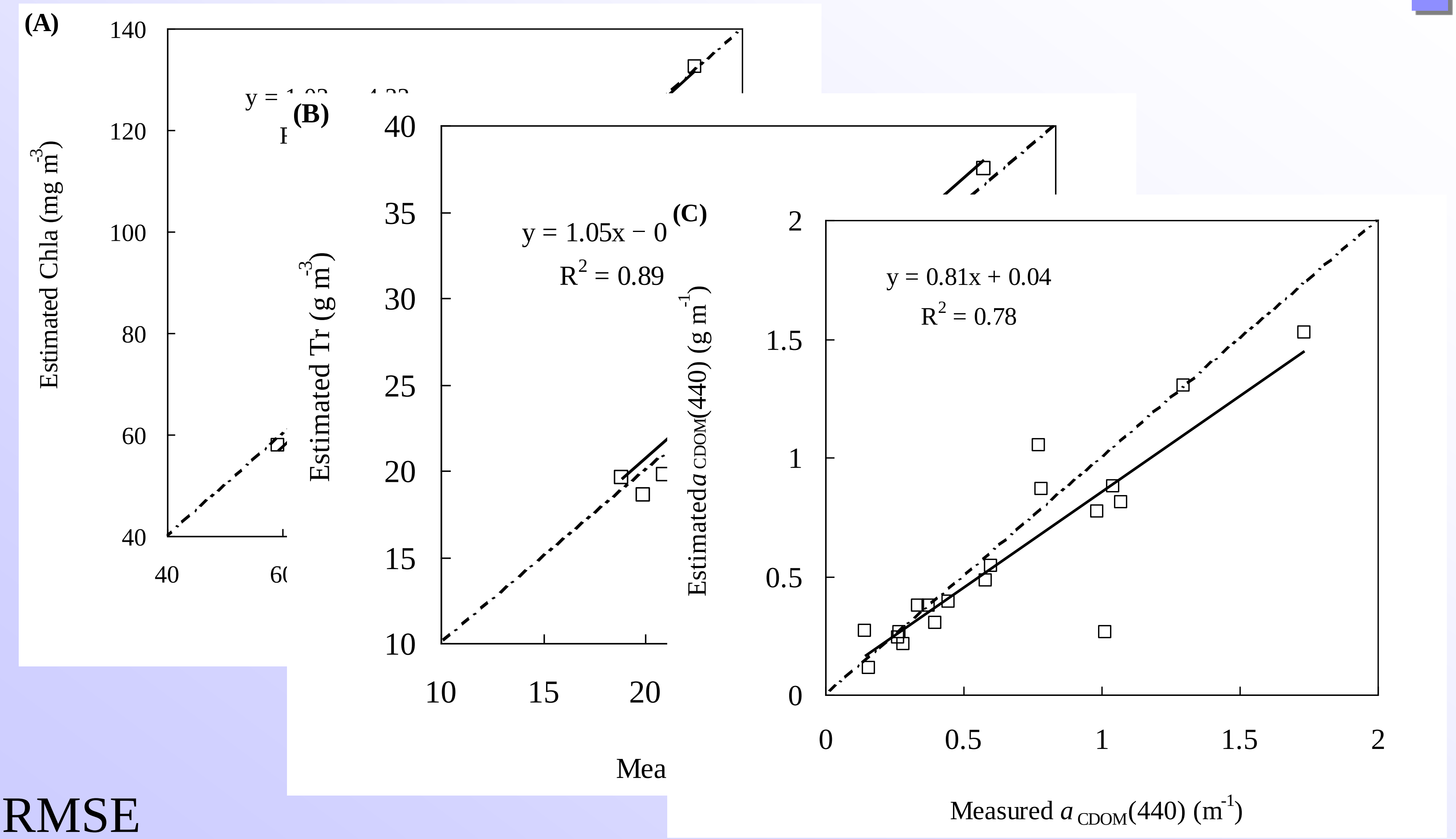


Validation results: By simulated data (noise-free)



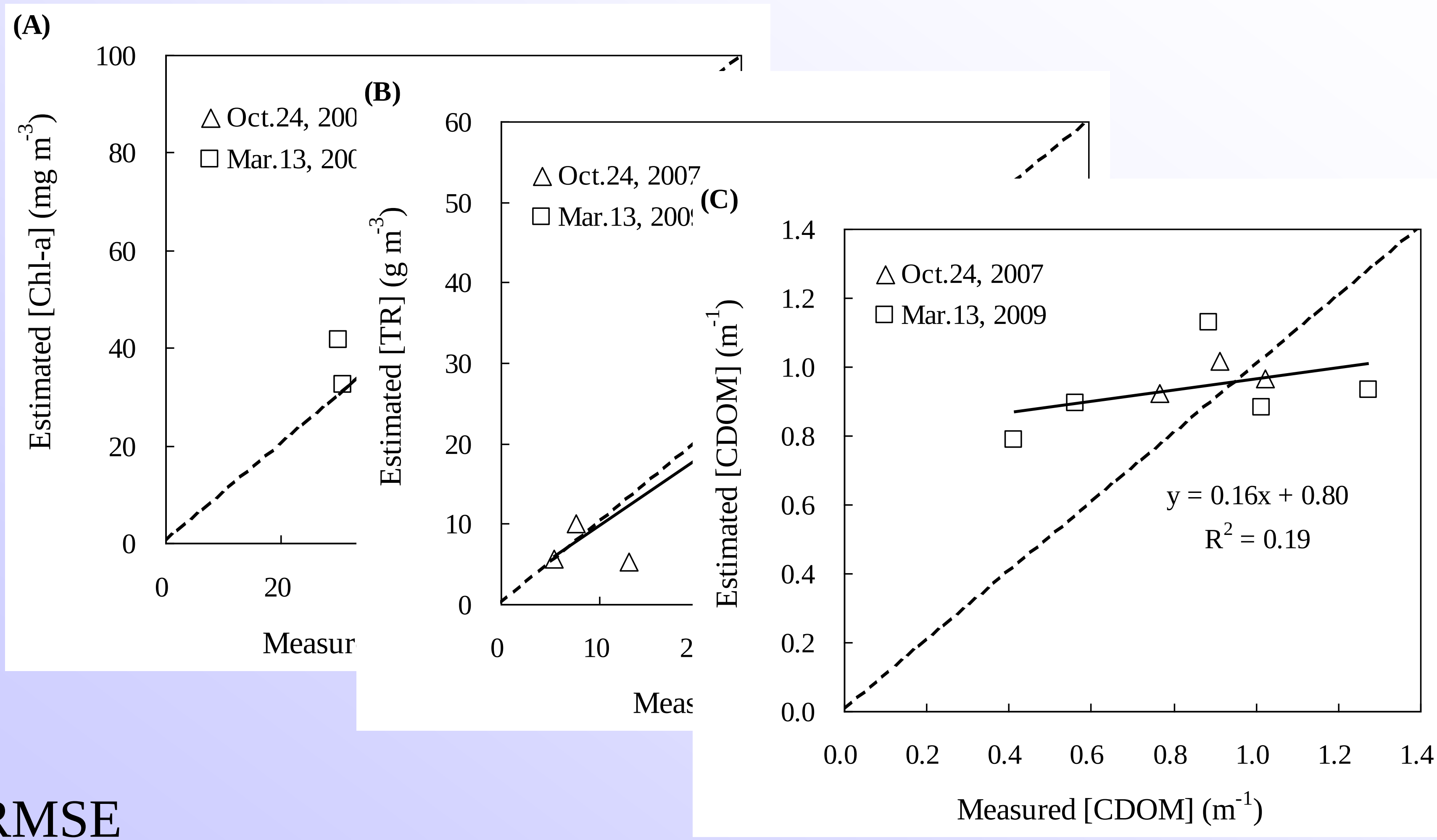
RMSE
（0.43,0.42,0.06）

Validation results: By *in situ* data (low noise)



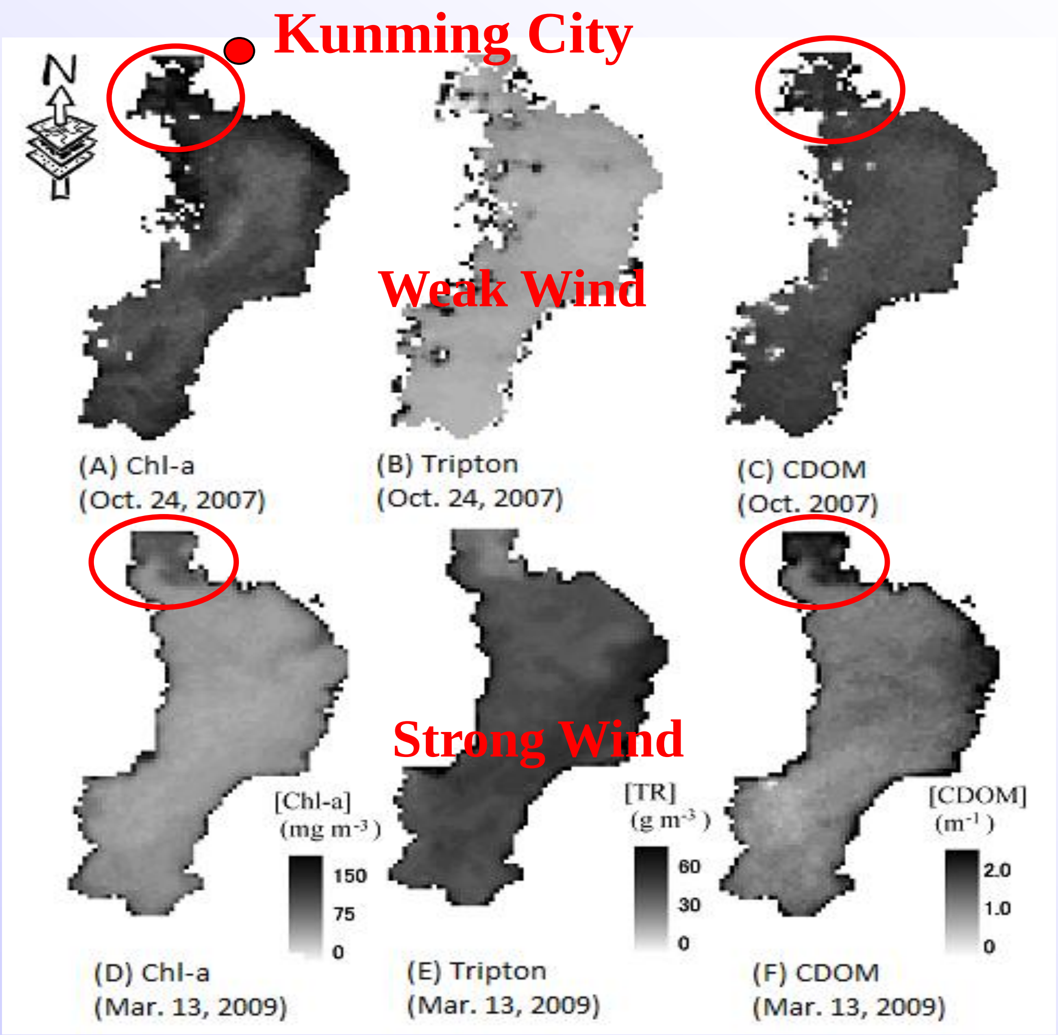
RMSE
（3.4,1.8,0.2）

Validation results: by MERIS data (high noise)



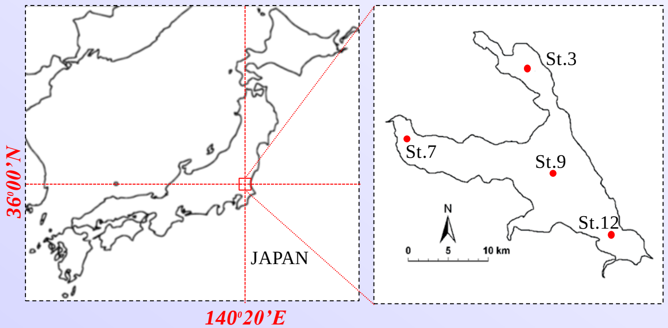
RMSE
(8.8, 6.9, 0.25)

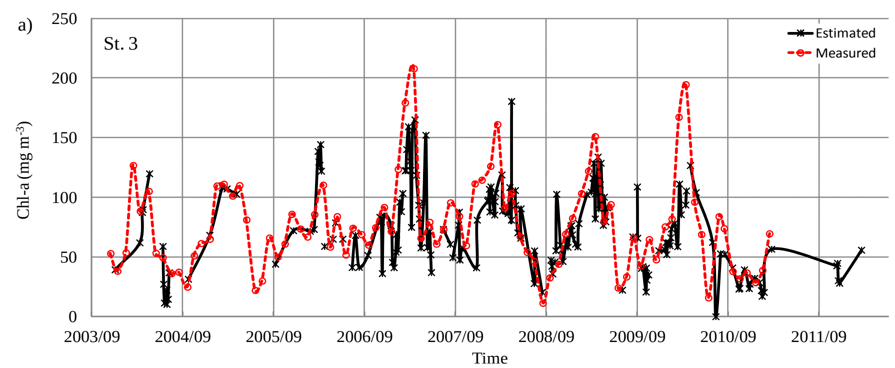
Spatial Distribution of Water Quality

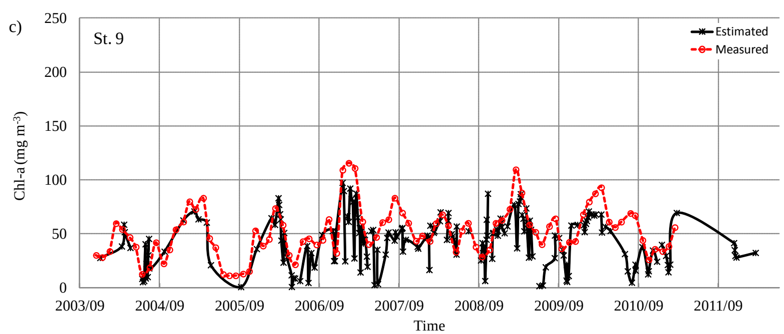


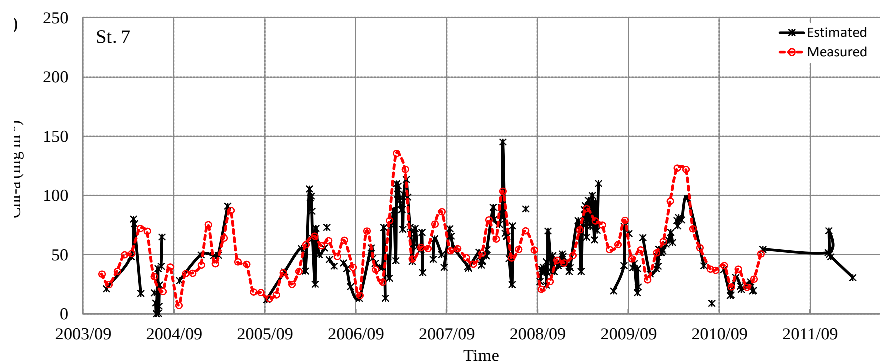
Long-term Monitoring in Lake Kasumigaura

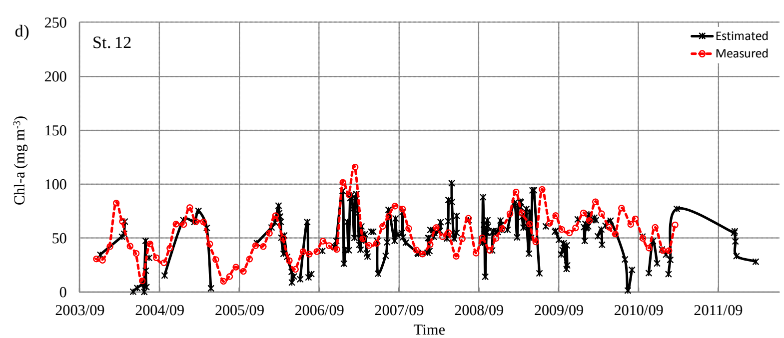
(Matsushita, Jaelania, **Yang** et al., 2015, RSSJ)





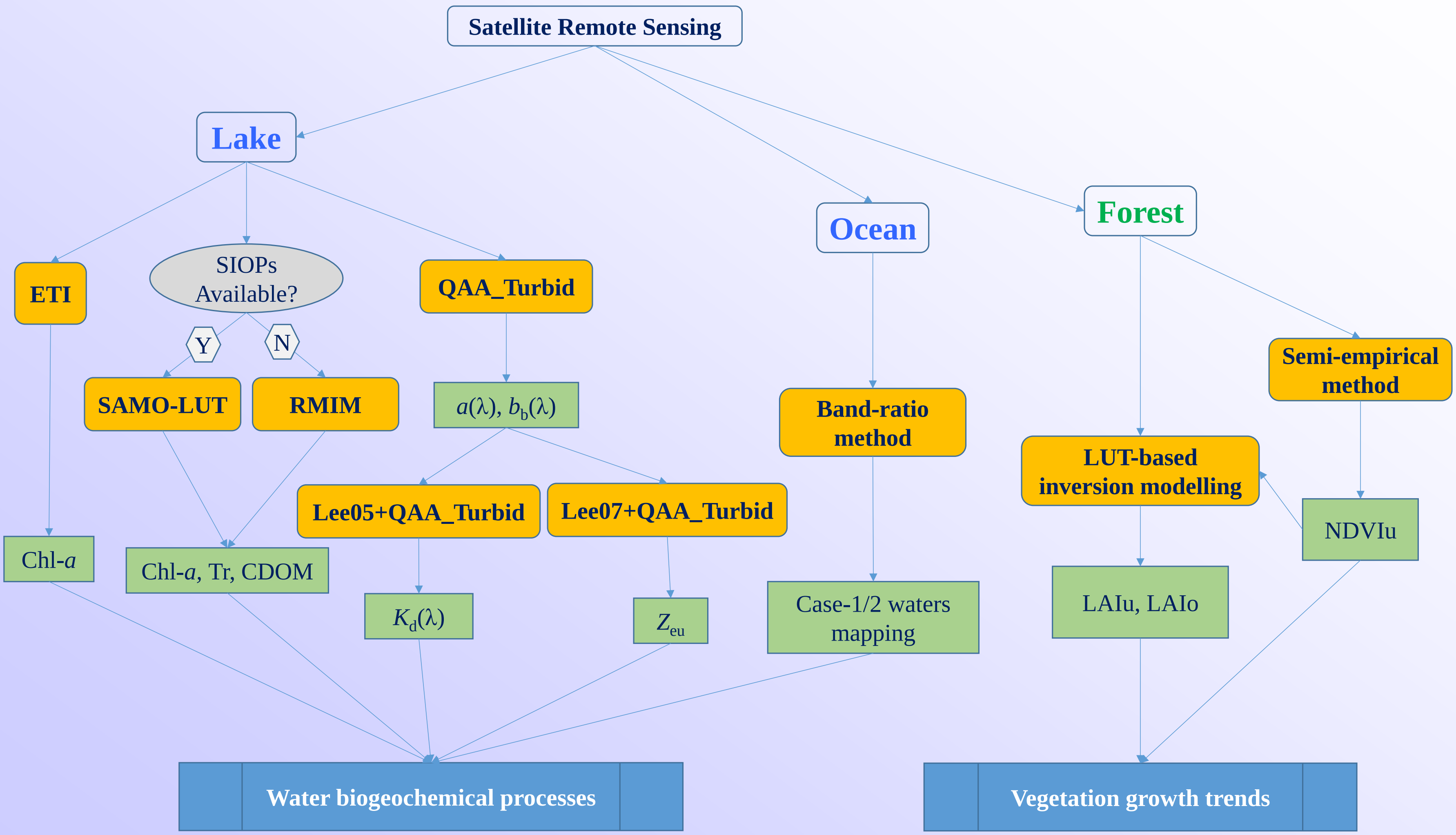






Time-series of satellite estimation show high agreements with field measurements.

Conclusions: my proposed algorithms



Take-home Messages

- Scientists in Chiba University, Japan are working on satellite monitoring of water quality.
- Our proposed algorithm worked well in long-term monitoring of water quality parameters in Japan’s lakes.
- We are challenging the continental/global monitoring of inland lakes, to aid the conventional investigations.

Thank you!