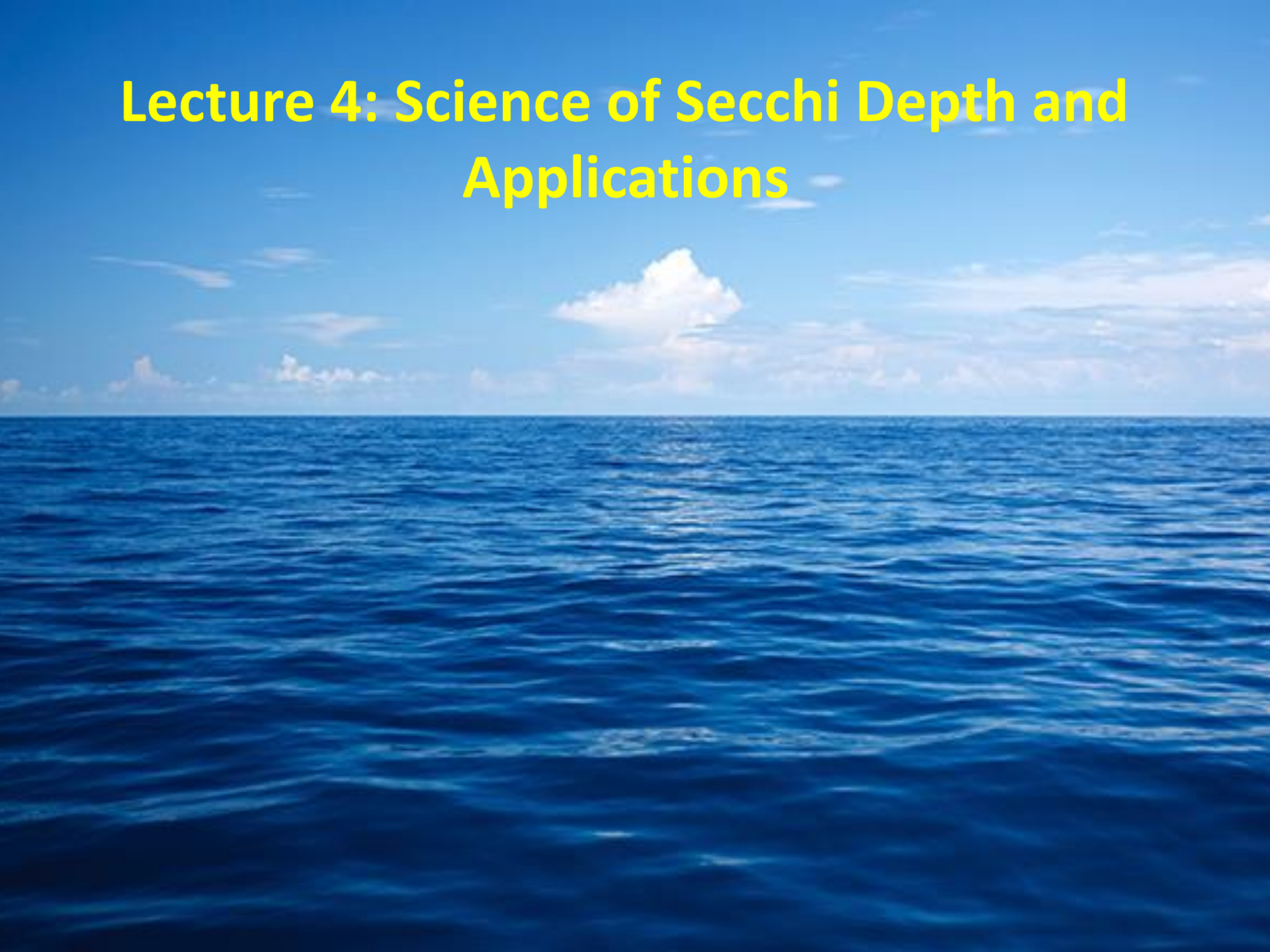
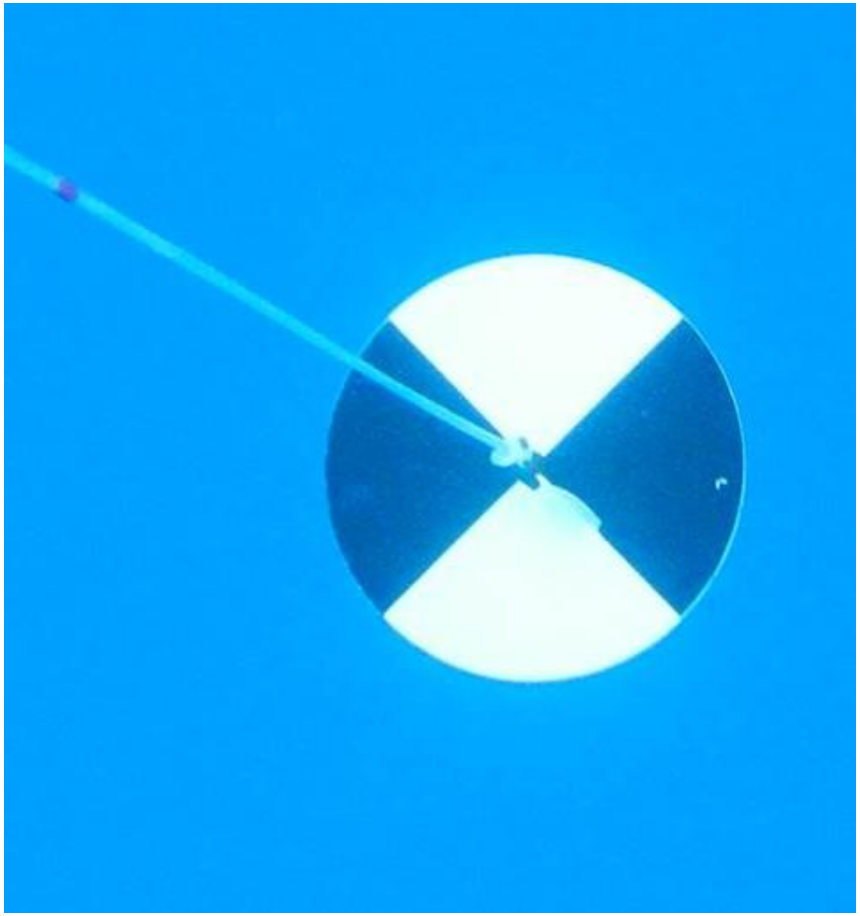
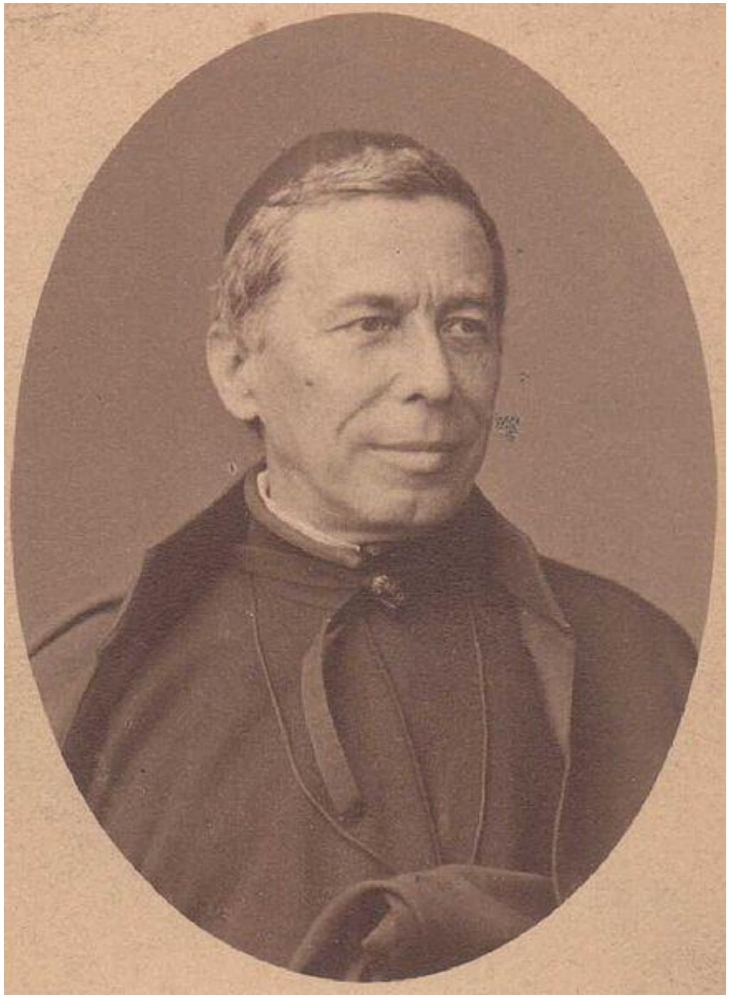
Lecture 4: Science of Secchi Depth and Applications

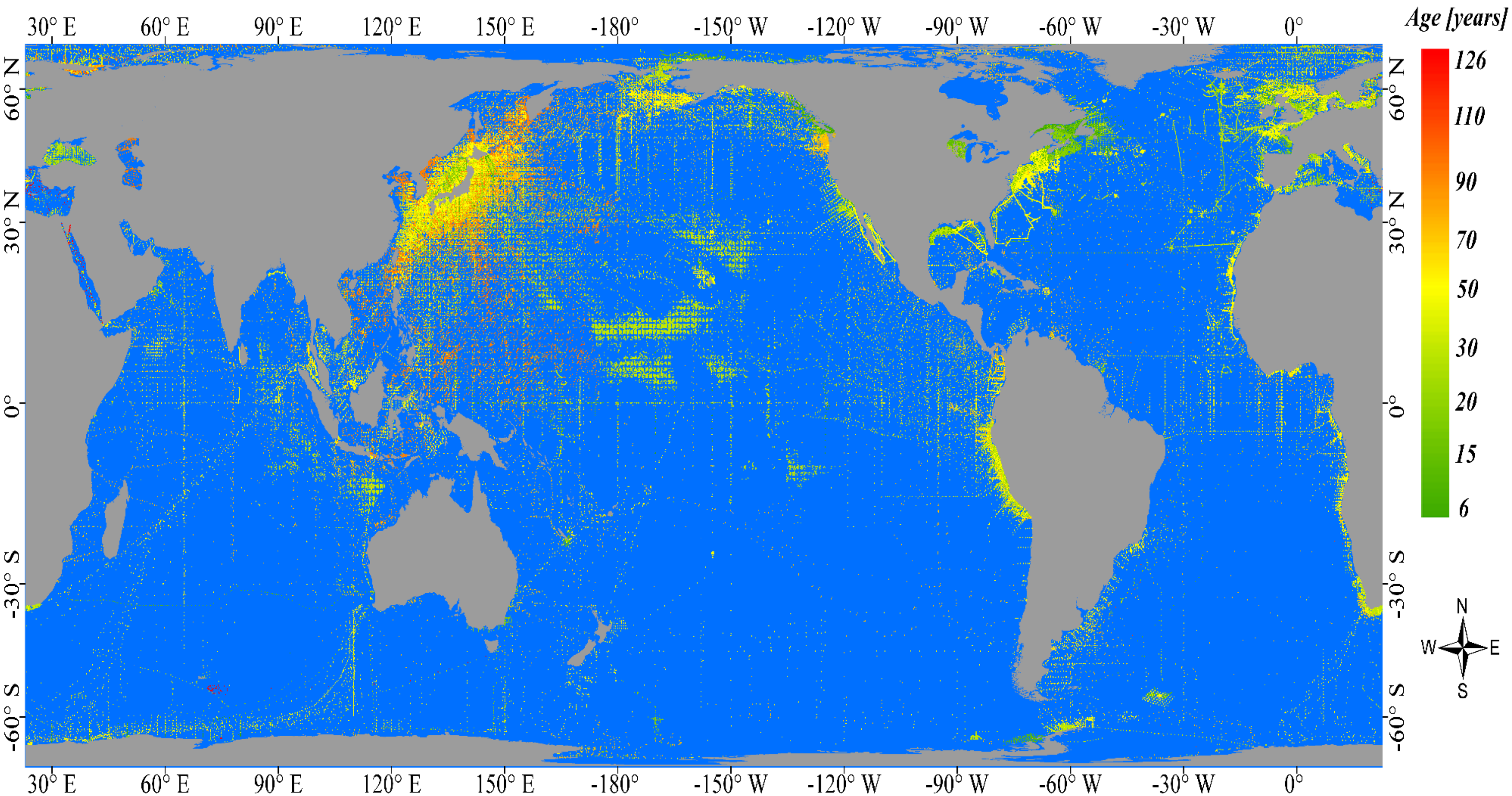


Water Clarity/Underwater Visibility





Angelo Secchi
(1818-1878)



Age [years]
126
110
90
70
50
30
20
15
6
30° E
60° E
90° E
120° E
150° E
-180°
-150° W
-120° W
-90° W
-60° W
-30° W
0°
60° N
30° N
0°
-30° S
-60° S
N
W
E
S

Can I see my toe?

Water quality monitoring by CrowdScience

Formula	Z_{SD} range (m)	Reference
$Z_{SD} = 1.7/K_{PAR}$	1.9 - 35	Poole and Atkins (1929)
$Z_{SD} = 1.44/K_{PAR}$	2 - 12	Holmes (1970)
$Z_{SD} = 1.7/K_{PAR}$	0.1 - 35	Idso (1974)
$Z_{SD} = 1.54/K_{PAR}$	6 - 46	Megard and Berman (1989)
$Z_{SD} = 1.27/K_{PAR}$	0.2 – 2.2	Gallegos et al. (1990)
$Z_{SD} = 1.86/K_{PAR}$	2.3 – 14.7	Kolengings et al. (1991)
$Z_{SD} = 1.4/K_{PAR}^{0.9}$	1.2 - 5	Montes-Hugo et al. (2005)
$Z_{SD} = 1.36/K_{PAR}$	0.1 - 42	Lugo-Fernandez (2008)
$Z_{SD} = 1.7/K_{PAR}1.3$	0.2 - 6	Padial and Thomaz (2008)
$Z_{SD} = 1.8/K_{PAR}$	0.6 – 4.2	Bracchini et al. (2009)
$Z_{SD} = 1.6/K_{PAR}^{1.1}$	1.7 – 7.0	Ficek and Zapadka (2010)
$Z_{SD} = 1.4/K_{PAR}$	0.5 – 2.5	Gallegos et al. (2011)
$Z_{SD} = 1.37/K_{PAR}$	0.1 – 2.4	Zhang et al. (2012)

>90 years of observations → Z_{SD} is a function of K_{PAR}

The classical theoretical relationship:

(Duntley 1952; Preisendorfer 1986; Zaneveld and Pegau 2003; Aas 2014)

$$Z_{SD} = \frac{\Gamma}{K_d + c}$$

$c >> K_d$

$$\Gamma = \ln\left(\frac{C_i}{C_t}\right)$$

(~5 – 10)

$$C_i = \frac{r_T - r_w}{r_w}$$

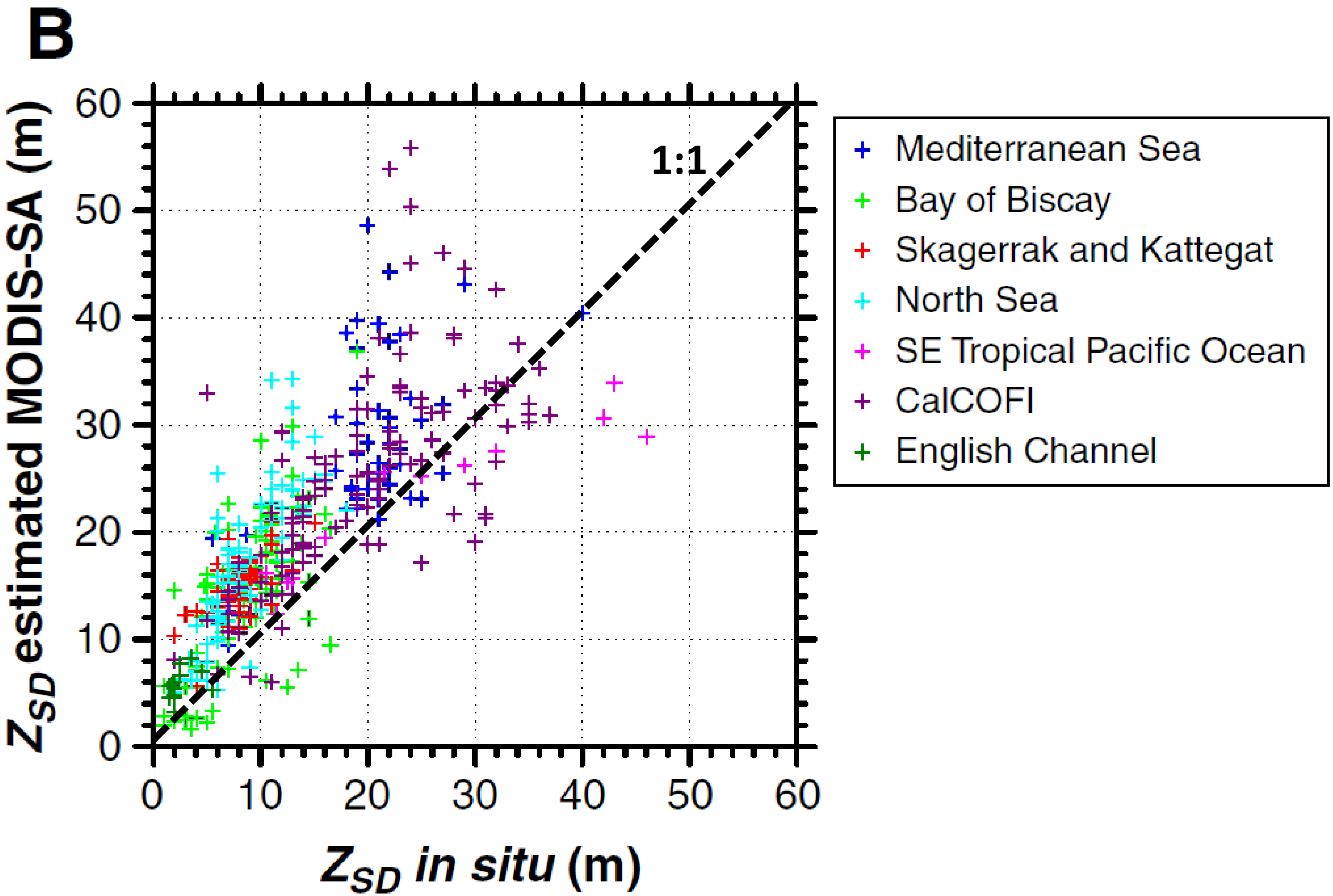
K_d: Diffuse attenuation coefficient

c: Beam attenuation coefficient

C_i: Inherent contrast

C_t: Contrast threshold of human eye; ~2%

Results via theory-based algorithm



(Doron et al 2011)

Theory-based model did not perform well, and does not match relationships from measurements …

How could this be?!

Three issues/ "mistakes" in the classical interpretation of Z_{SD}:

1. Spectrally-weighted attenuation

2. Evaluation of contrast

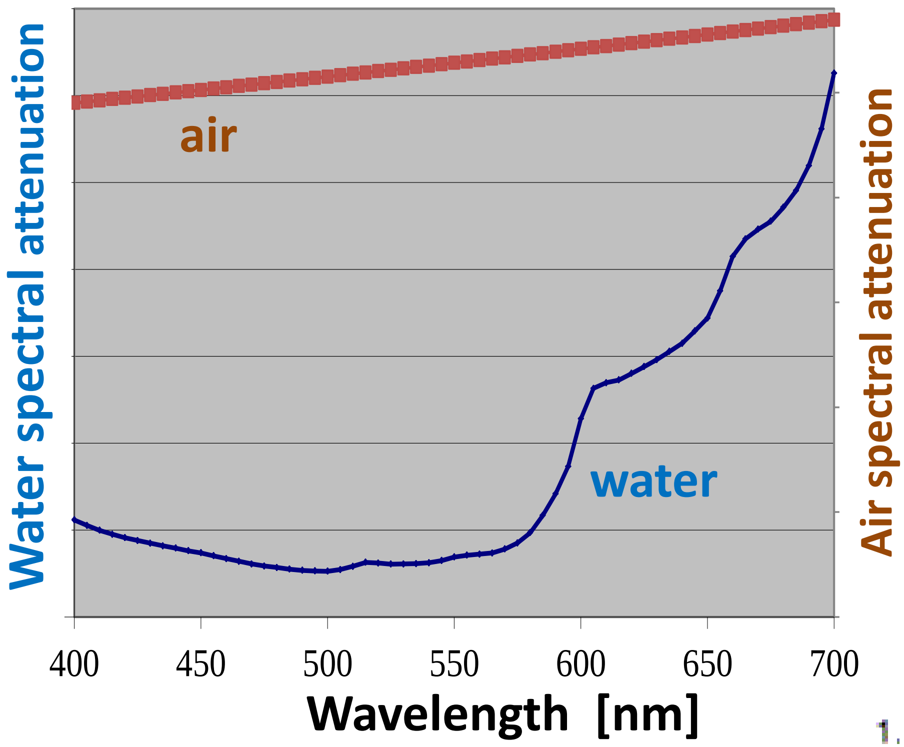
3. *c* for contrast attenuation

1. Spectrally-weighted attenuation

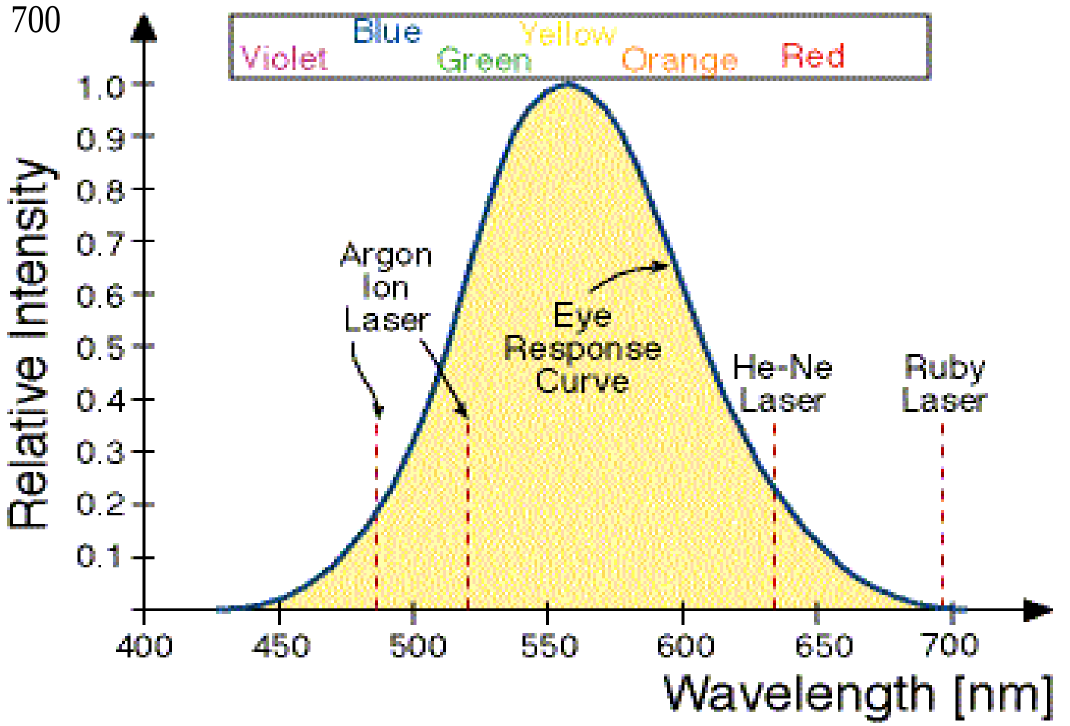
$$Z_{SD} = \frac{\Gamma}{K_d + c}$$

K_d and c are quantities based on photometric quantity weighted by the response function of our eyes, ie **assumed we use the entire visible band for this detection …**

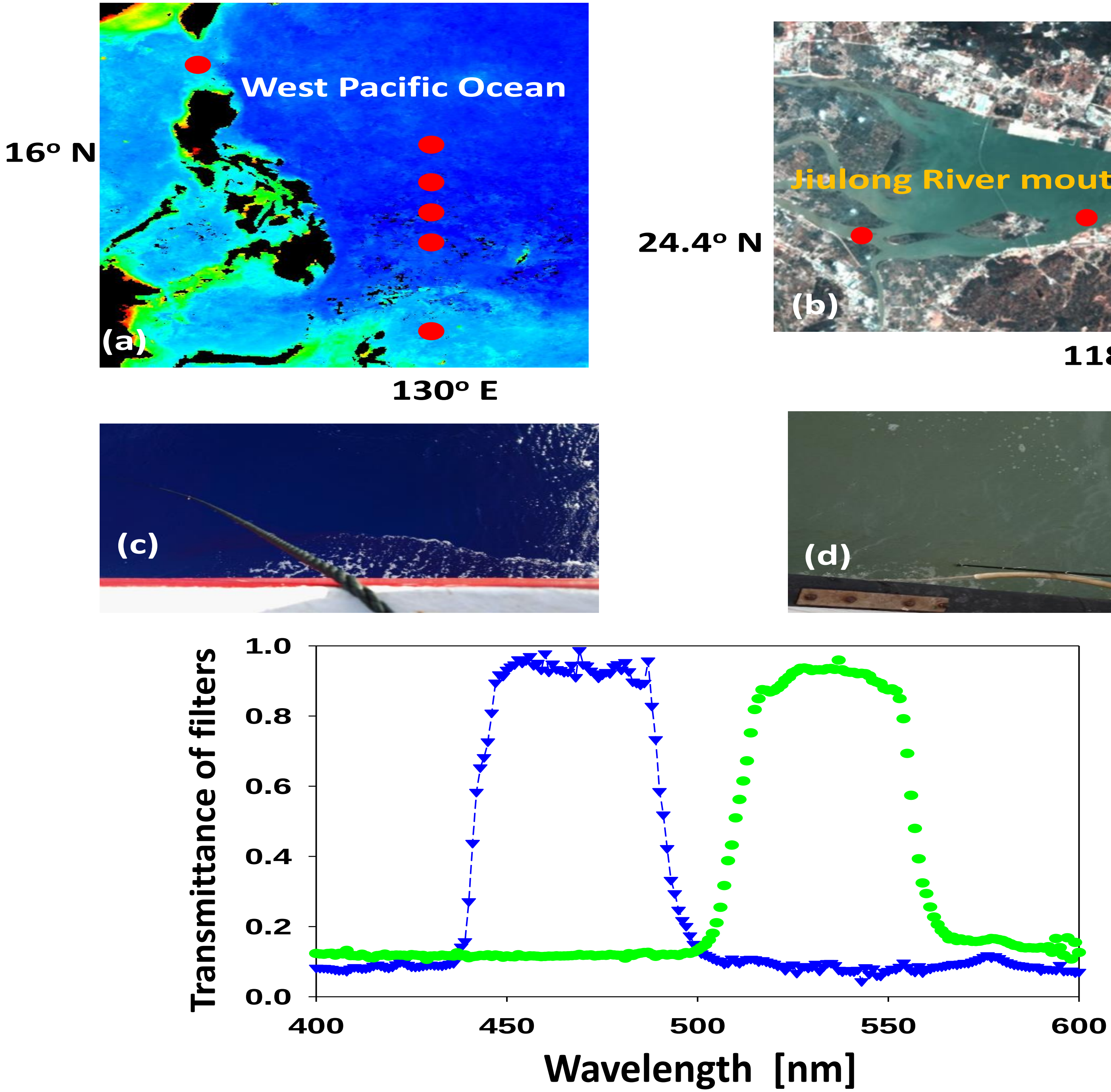
$$N = \int_{\lambda_{vis}} L \, R_{eye} \, d\lambda$$

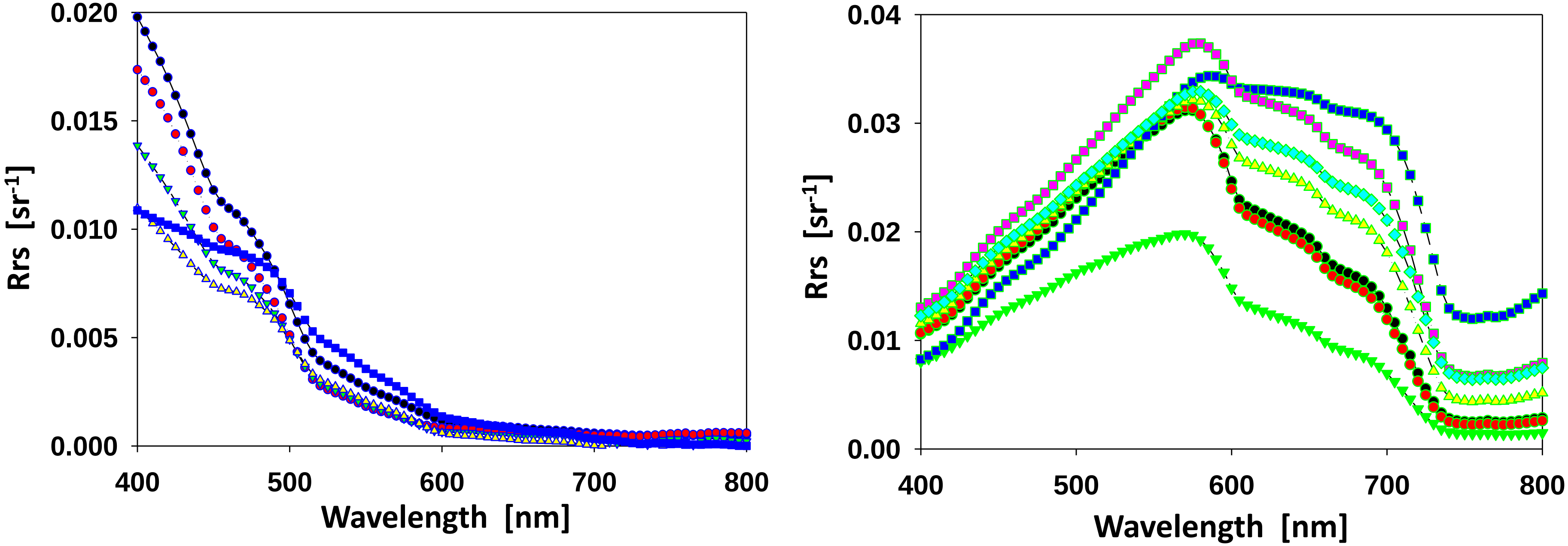


Water spectral attenuation
Air spectral attenuation
air
water
400
450
500
550
600
650
700
Wavelength [nm]

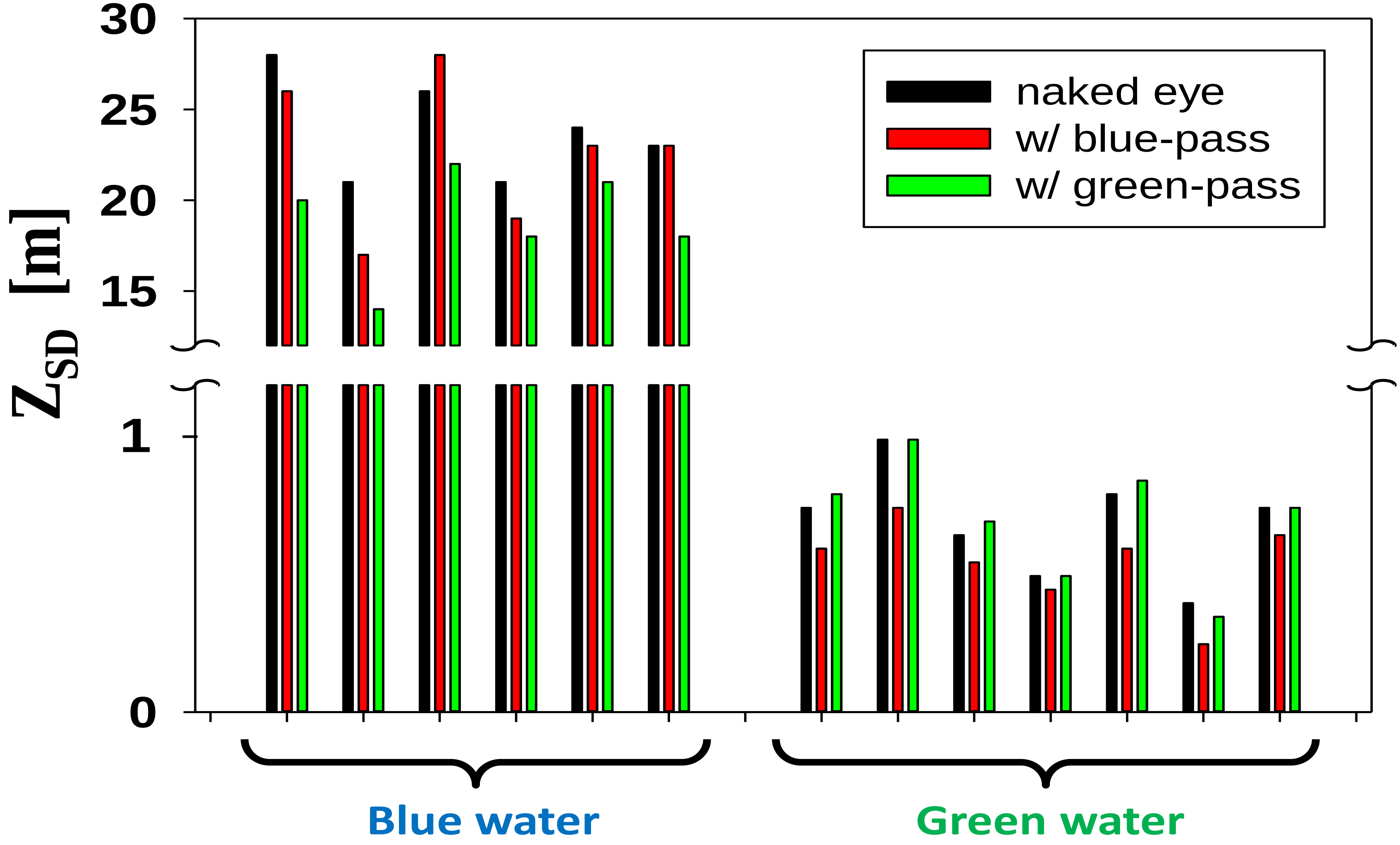


Violet
Blue
Green
Yellow
Orange
Red
Relative Intensity
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
Argon Ion Laser
Eye Response Curve
He-Ne Laser
Ruby Laser
400
450
500
550
600
650
700
Wavelength [nm]


West Pacific Ocean
16° N
130° E
(a)
Jiulong River mouth
24.4° N
118° E
(b)
(c)
(d)
Transmittance of filters
1.0
0.8
0.6
0.4
0.2
0.0
400
450
500
550
600
Wavelength [nm]



Rrs [sr-1]
0.020
0.015
0.010
0.005
0.000
400
500
600
700
800
Wavelength [nm]
Rrs [sr-1]
0.04
0.03
0.02
0.01
0.00
400
500
600
700
800
Wavelength [nm]



Z_{SD} [m]
30
25
20
15
1
0
naked eye
w/ blue-pass
w/ green-pass
Blue water
Green water

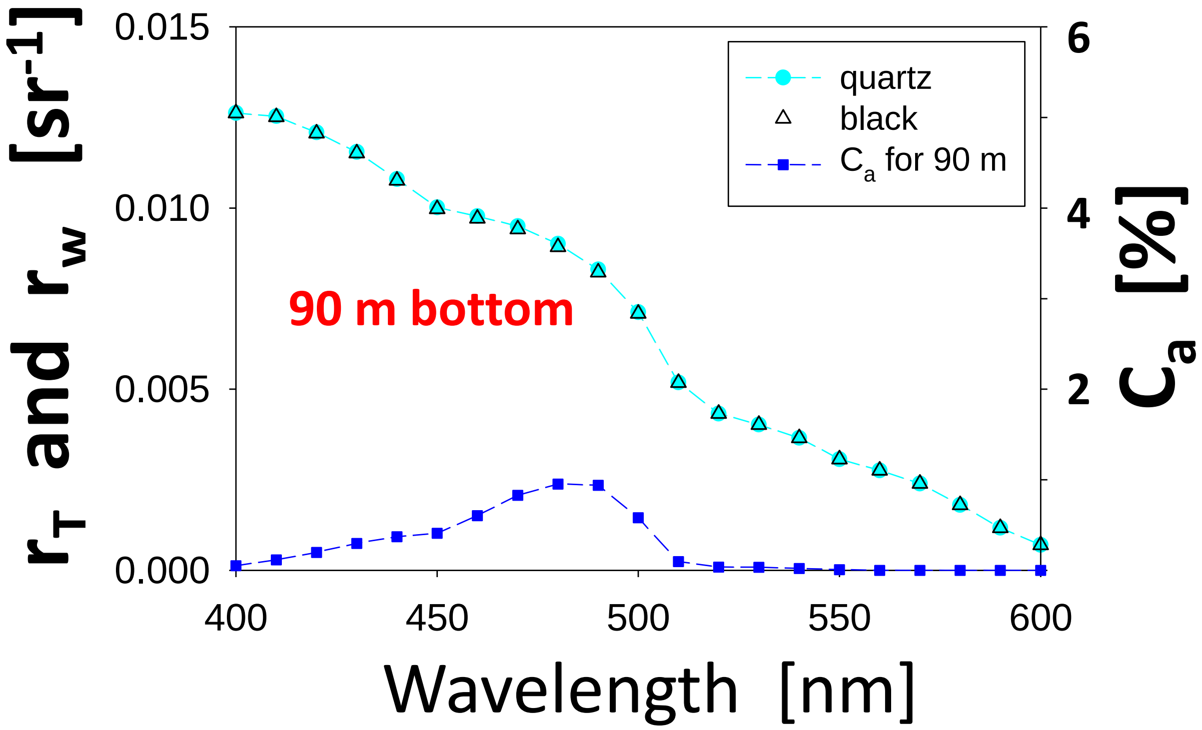
Ratio of Z_{SD} with color filters (Z_{SD}^{b} , Z_{SD}^{g}) to Z_{SD}, and ratio of Z_{SD}^{b} to Z_{SD}^{g}

	Blue water (N = 6)	Green water (N = 7)
Blue-pass glasses	0.95±0.09 (0.81-1.08)	0.79±0.09 (0.63-0.90)
Green-pass glasses	0.79±0.08 (0.67-0.88)	1.01±0.07 (0.88-1.08)
Blue-pass to green-pass	1.20±0.10 (1.06-1.30)	0.78±0.07 (0.71-0.90)

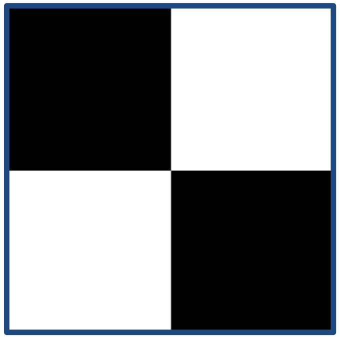
We detect targets in water using the transparent window, not the entire visible band.

2. Evaluation of contrast

$$C_a(z) = \frac{L_T(z) - L_w(z)}{L_w(z)} = \frac{r_T(z) - r_w(z)}{r_w(z)}$$



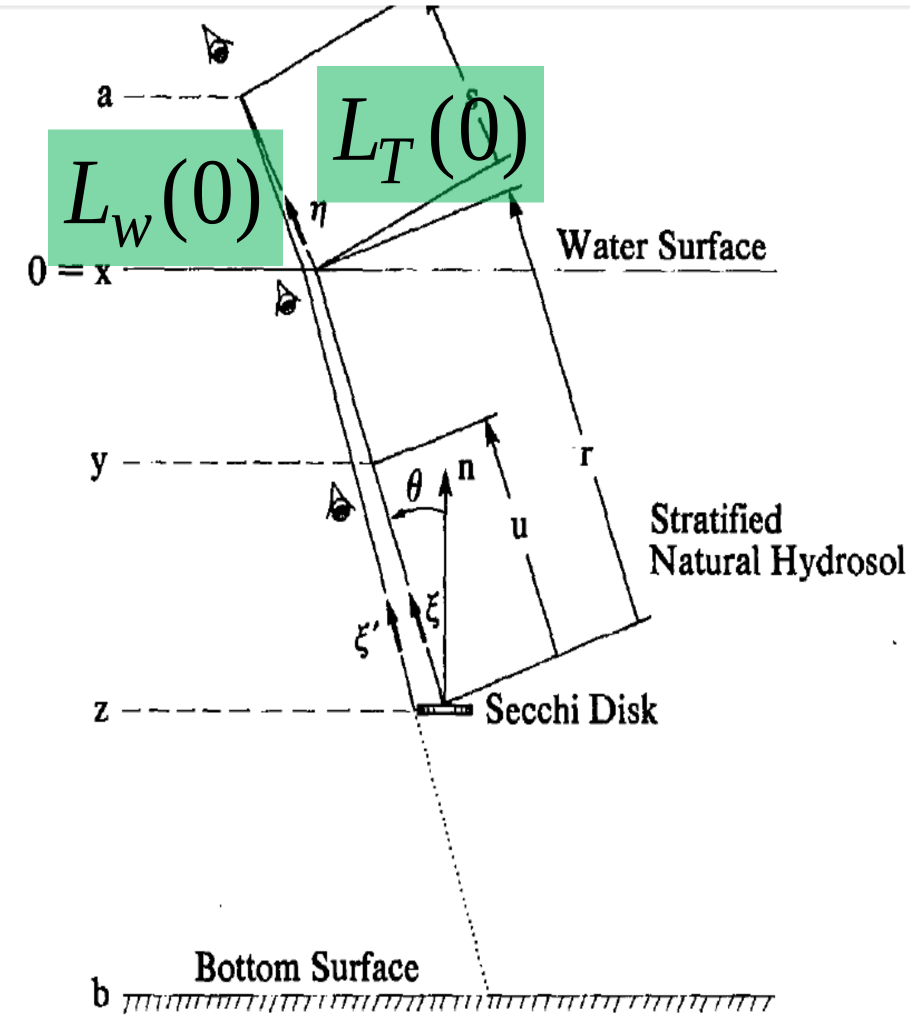
Evaluation of contrast



$$\left(\frac{r_T - r_w}{r_w}\right)$$

Classical evaluation of contrast is not consistent with the judgement decision by eye-brain system.

3. *c* for contrast attenuation



Geometry of the Secchi Disk Sighting

(Preisendorfer, 1986)

contrast:

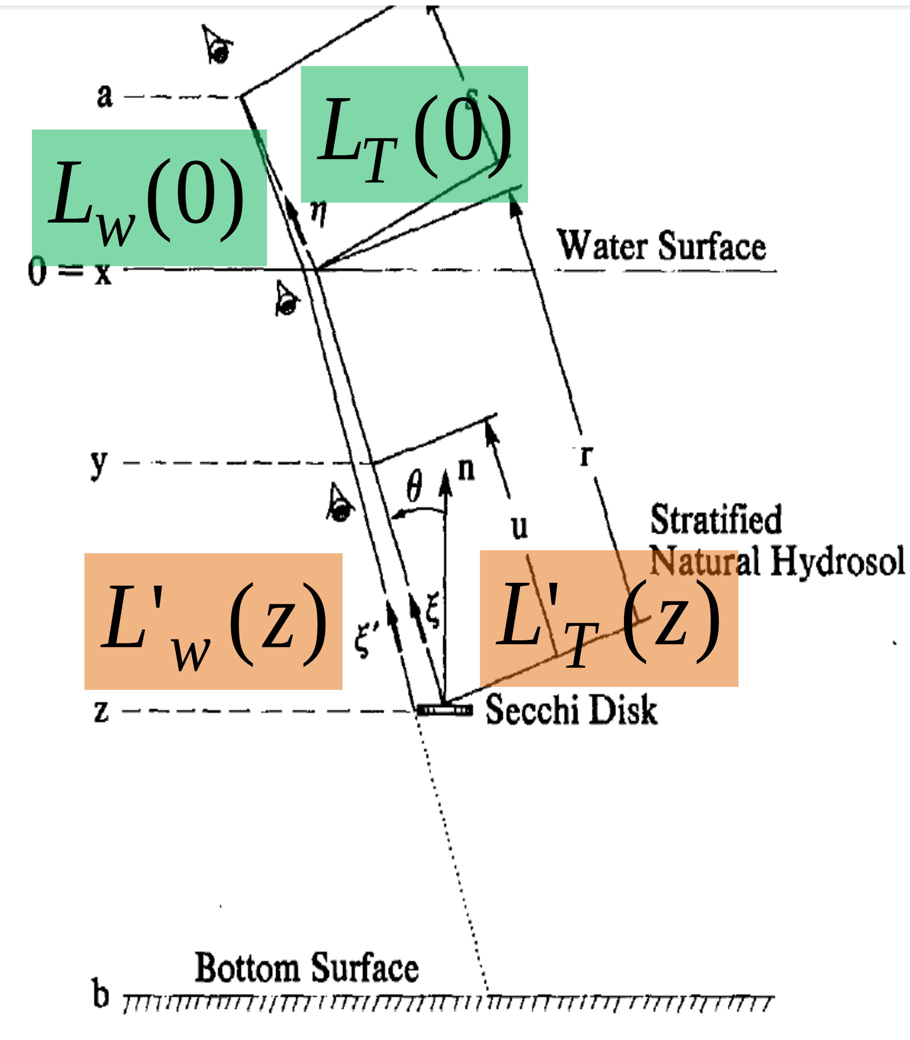
$$C_a(z) = \frac{L_T(z) - L_W(z)}{L_W(z)}$$

Detection limit:

$$C_a = C_t$$

Threshold of human eyes; ~2%

Derivation of contrast attenuation



Geometry of the Secchi Disk Sighting

(Preisendorfer, 1986)

Radiative transfer:

$$d\frac{L_T(z,\xi)}{dz} = -c\,L_T(z,\xi) + \int_{4\pi} L'_T(z)\beta d\omega$$

$$d\frac{L_W(z,\xi')}{dz} = -c\,L_W(z,\xi') + \int_{4\pi} L'_W(z)\beta d\omega$$

Assume:

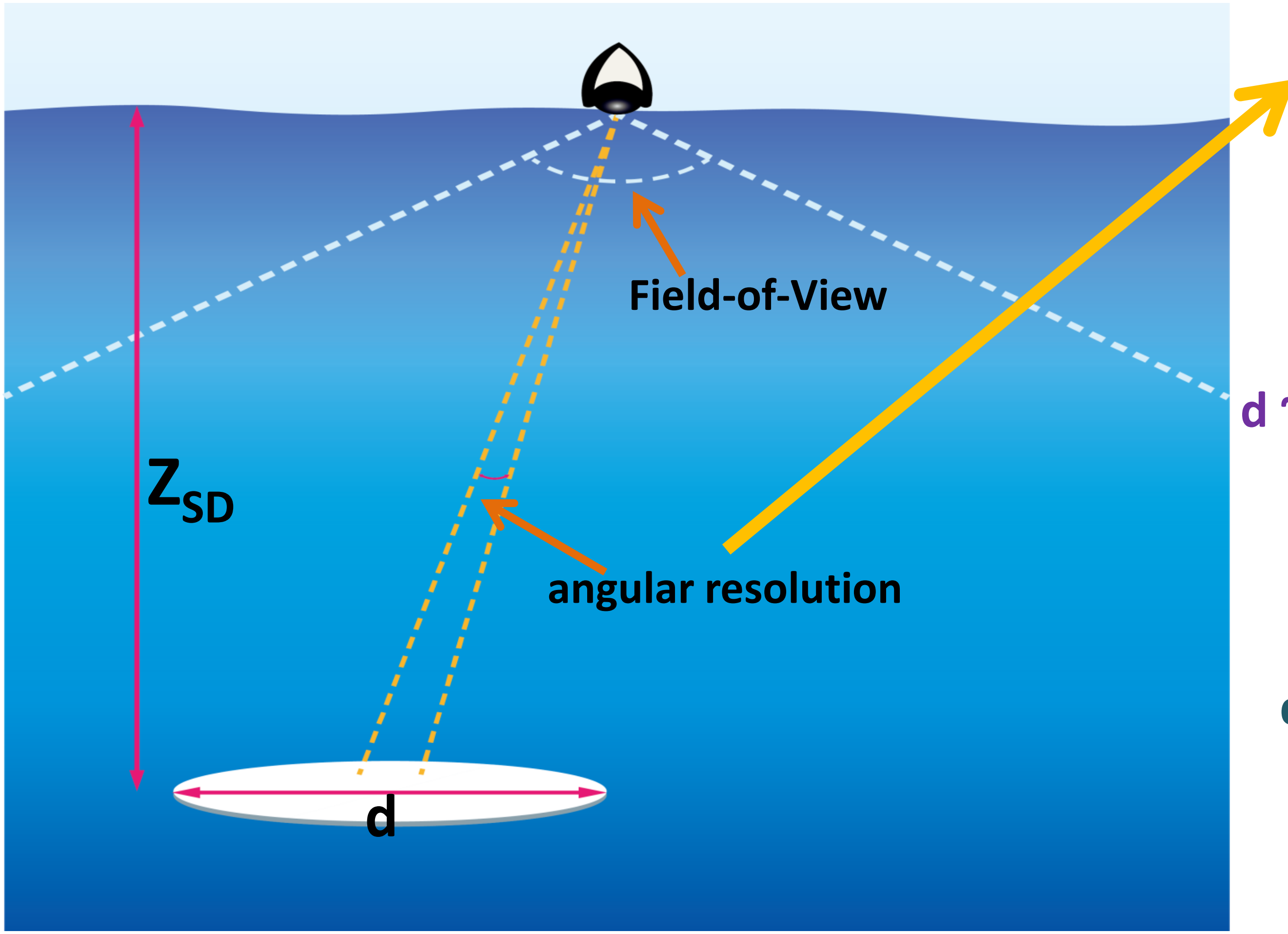
$$\int L'_T(z)\beta\,dw = \int L'_w(z)\beta\,dw$$

$$d\frac{L_T(z) - L_W(z)}{dz} = -c\left(L_T(z) - L_W(z)\right)$$

$$Z_{SD} = \frac{\Gamma}{K_d + c}$$

A Secchi disk is assumed as a point target for human eye!

Secchi disk vs the resolution of eye "sensor"



~0.5 Arcmin

~0.2 mm for a distance of 1 m

d ~ 1500 * eye resolution

Z_{SD}: up to ~50 m

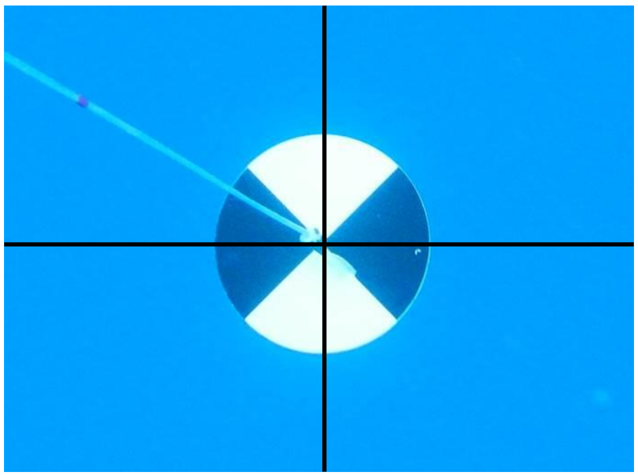
d ~ 30 * eye resolution

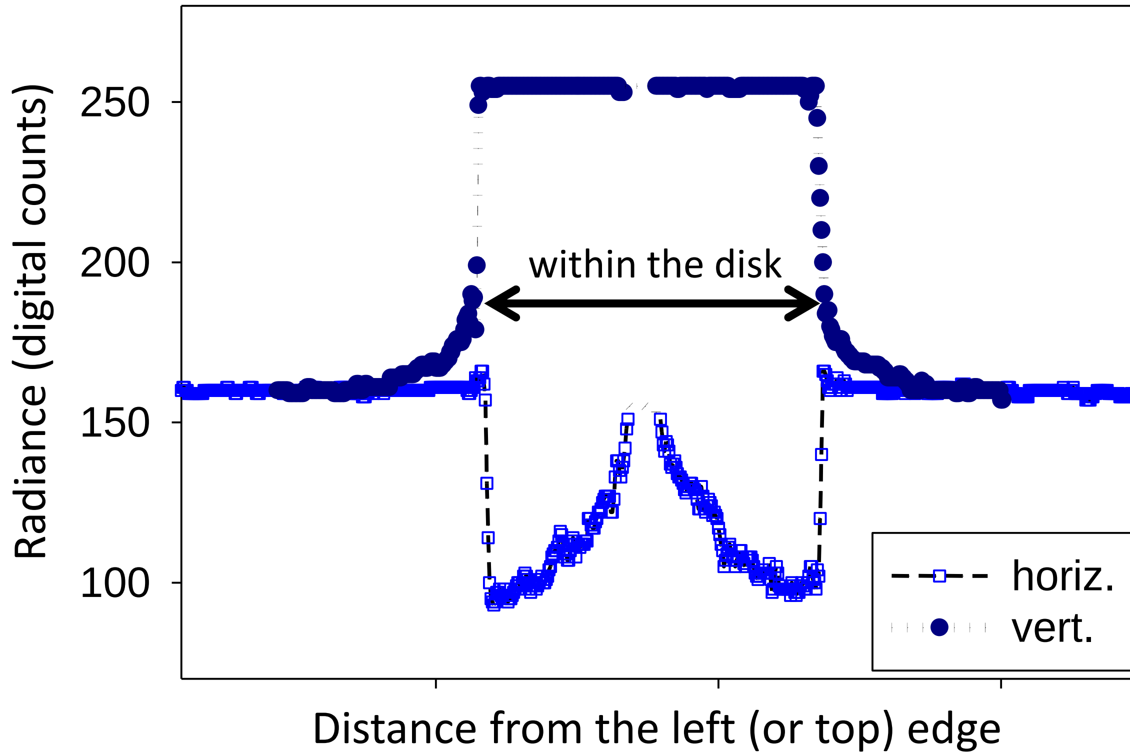
For a radiance sensor with a 5° resolution, the equivalent target is ~ 120-m wide when viewed 1 m away.

➡ A Secchi disk is **NOT** a point source for human eyes.

Point source: $$L'_T(z) = L'_w(z)$$

Spatial variation of radiance around a Secchi disk:





$$\int L'_T(z)\,\beta\, dw \neq \int L'_w(z)\,\beta\, dw$$

Derivation of contrast attenuation

$$d\frac{L_T(z,\xi)}{dz} = -c\,L_T(z,\xi) + \int_{4\pi} L'_T(z)\,\beta d\omega$$

$$d\frac{L_w(z,\xi')}{dz} = -c\,L_w(z,\xi') + \int_{4\pi} L'_w(z)\,\beta d\omega$$

$$\int L'_T(z)\,\beta\,dw \neq \int L'_w(z)\,\beta\,dw$$

$$d\frac{L_T(z) - L_w(z)}{dz} \neq -c\left(L_T(z) - L_w(z)\right)$$

$$Z_{SD} \neq \frac{\Gamma}{K_d + c}$$

d ~ 50 * the resolution of "eye sensor"

⇓

A Secchi disk is a sinking "sea floor" to human eye

Radiative transfer of shallow bottom (Lee et al 1994, 1998):

$$L_T^{tr}(0-) = r_w^{tr}\, E_d^{tr}(0-)\left(1 - e^{-(K_d^{tr}+K_L^{tr})\,z}\right) + r_T\, E_d^{tr}(0-)\; e^{-(K_d^{tr}+K_L^{tr})\,z}$$

Adjacent water:

$$L_w^{tr}(0-) = r_w^{tr}\, E_d^{tr}(0-)$$

Contrast in radiance:

$$L^C = L_T^{tr}(0-) - L_w^{tr}(0-)$$

Eye-adapted Contrast:

$$C_a^n = \frac{L_T^{tr}(0-) - L_w^{tr}(0-)}{E_d(0-)}$$

⇒

$$C_a^n = \left(r_T - r_w^{tr}\right) e^{-(K_d^{tr}+K_L^{tr})z}$$

$$C_a^n = C_t^n$$

⇒ Z_{SD}

New theoretical relationship for Z_{SD}:

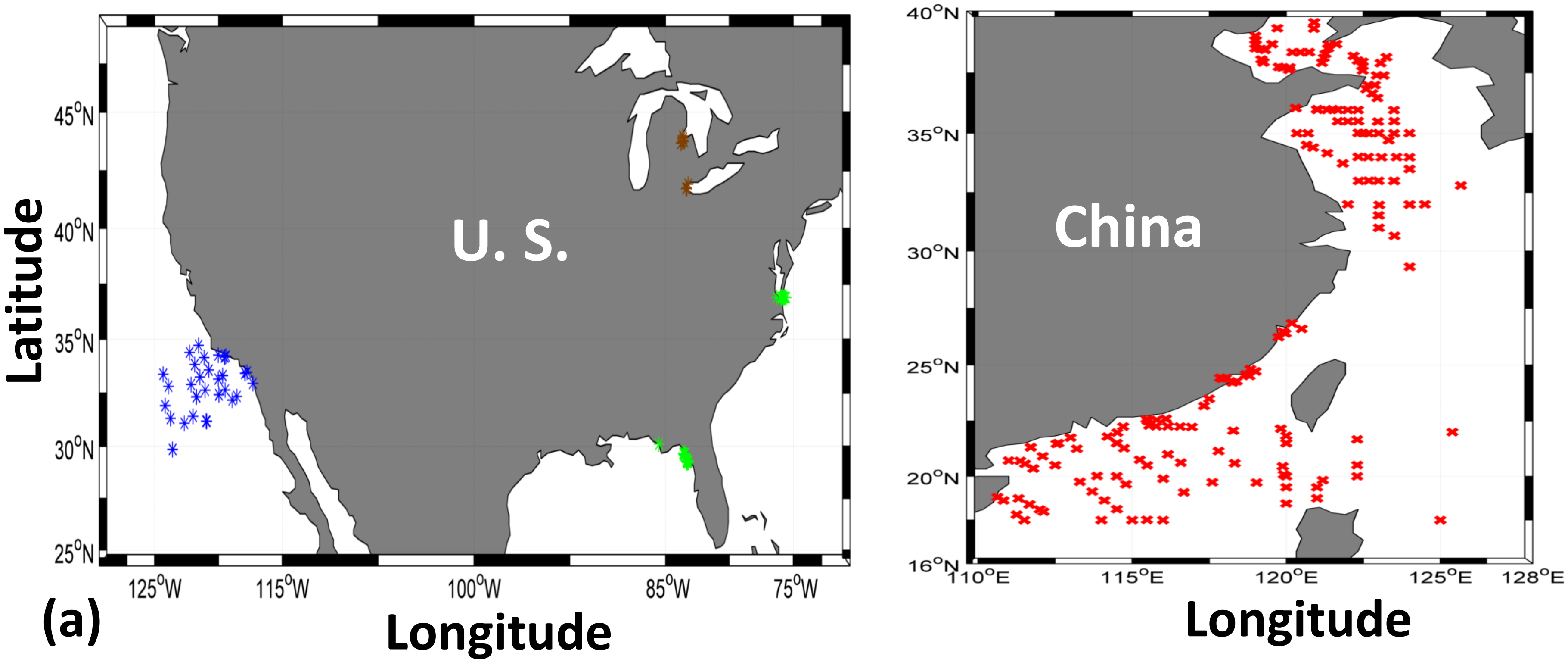
$$Z_{SD} = \frac{1}{K_d^{tr} + K_L^{tr}} \ln\left(\frac{1}{C_t^r} \left(r_T - r_w^{tr} \right) \right)$$

$$Z_{SD} \approx \frac{1}{2.5 K_d^{tr}} \ln\left(\frac{\left| r_T - r_w^{tr} \right|}{0.013} \right) \approx \frac{1}{K_d^{tr}}$$

K_d^{tr} **: attenuation coefficient in the transparent window**

(Lee et al 2015)

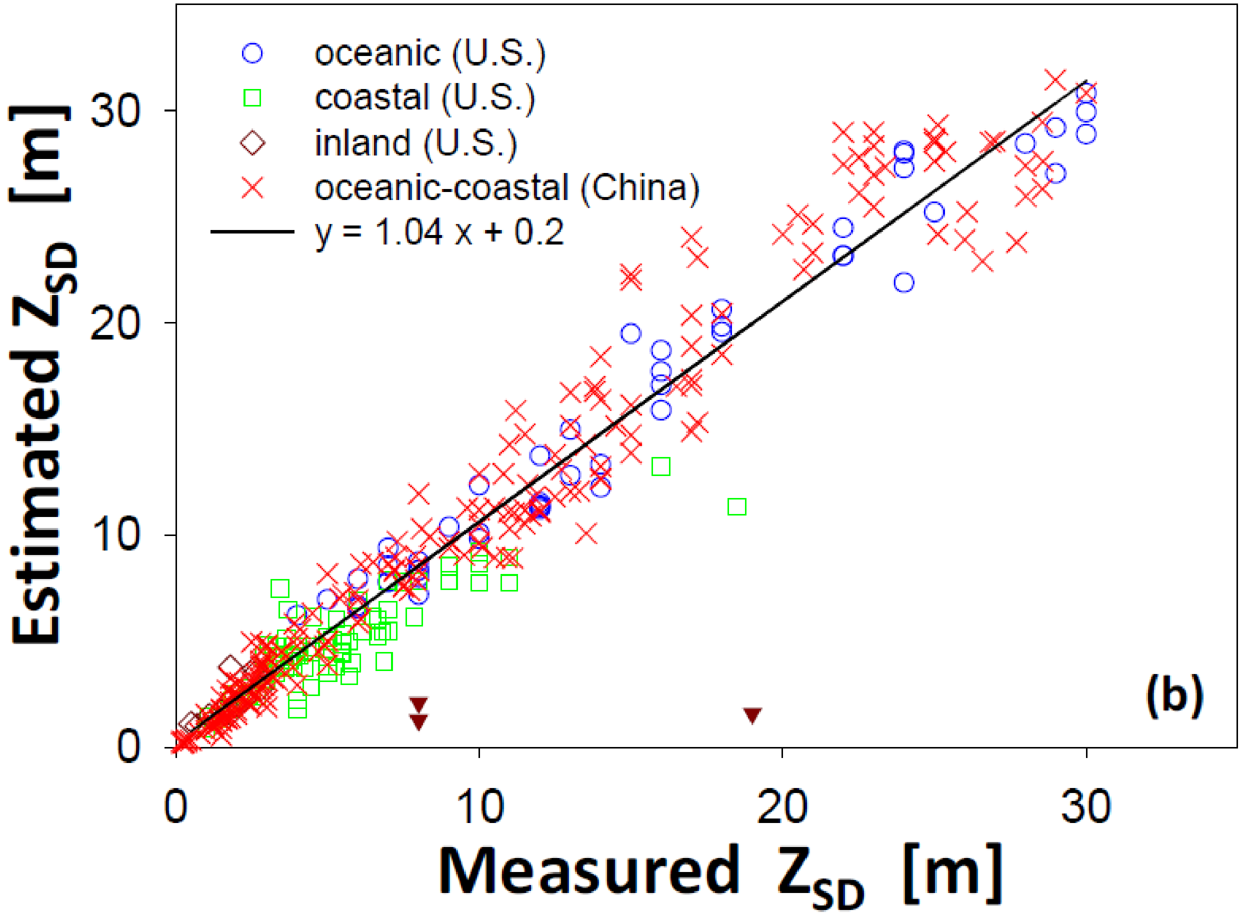
Verification of the new Secchi disk theory



QAA Lee et al 2013

$$R_{rs} \rightarrow a\&b_b \rightarrow K_d$$

Verification of the new Secchi disk theory

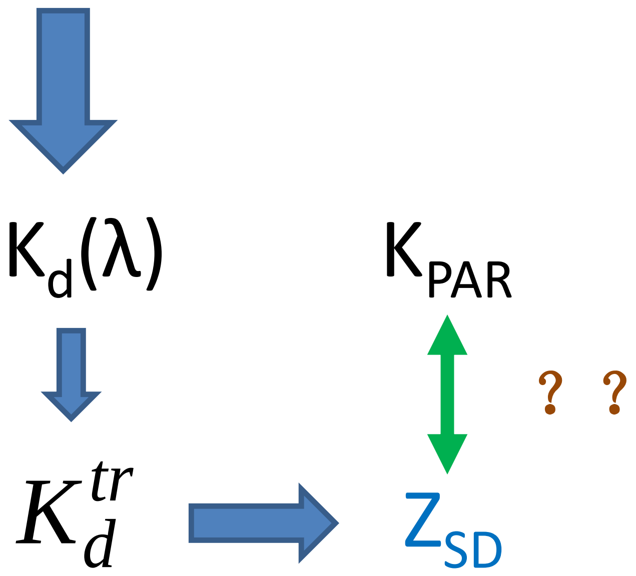


With K_d^{tr} as the minimum K_d among 410, 440, 490, 530, and 550 nm

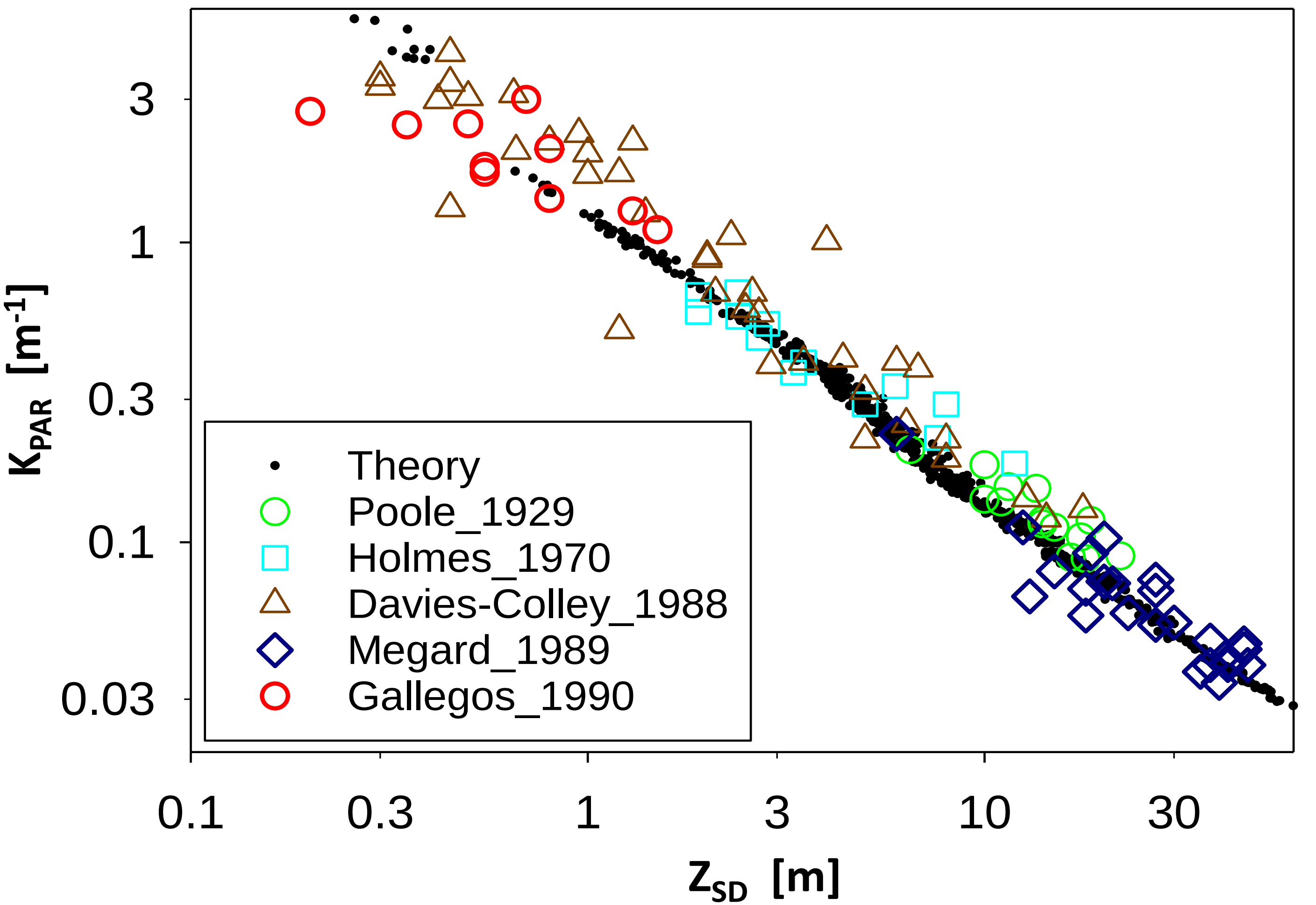
(Lee et al 2015)

Can the new theory explain historical data?

Hydrolight simulations with a wide range of IOPs (a440 ~ 0.001 – 50 m^{-1})

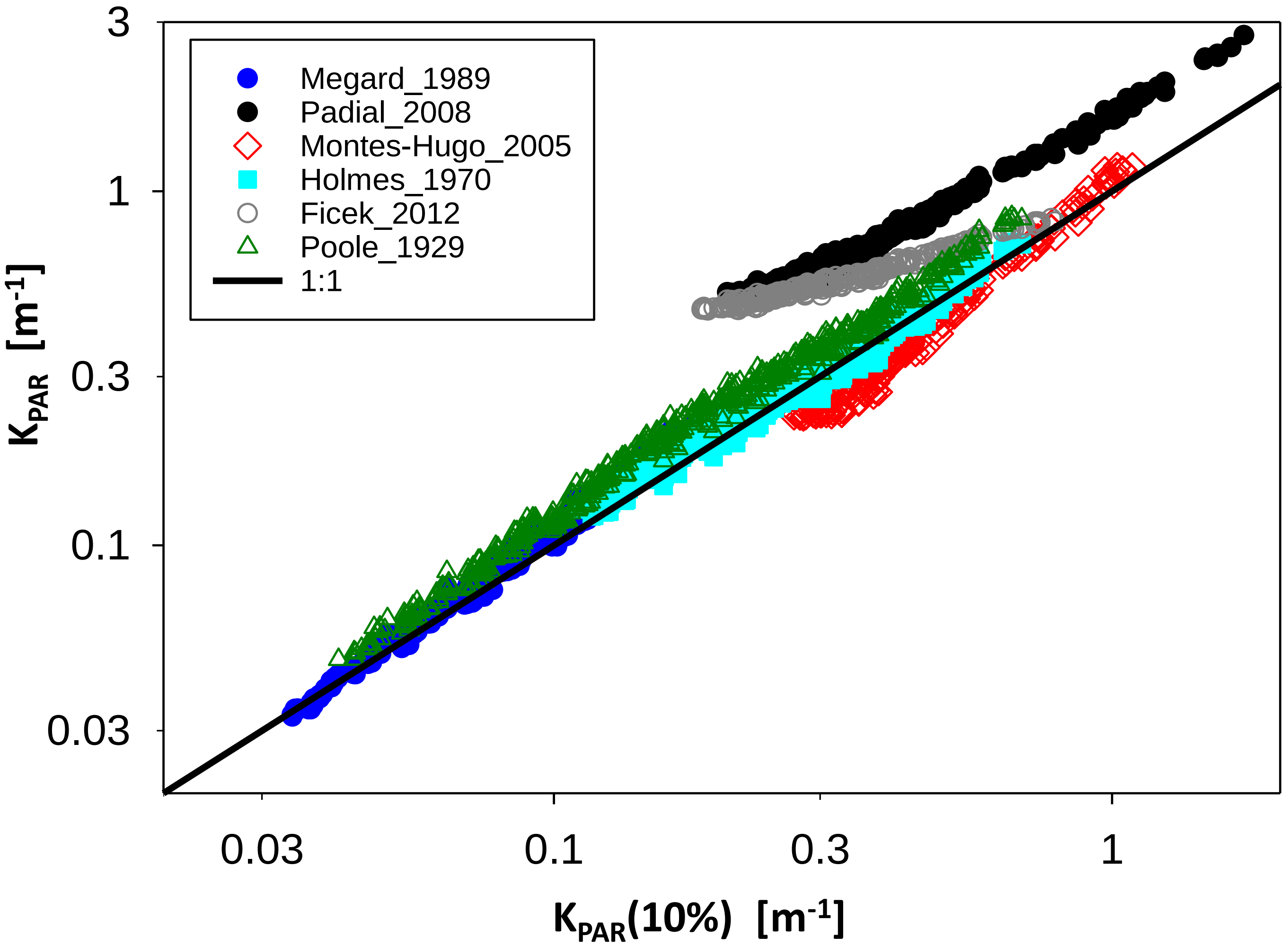


Comparison between simulated and observed data



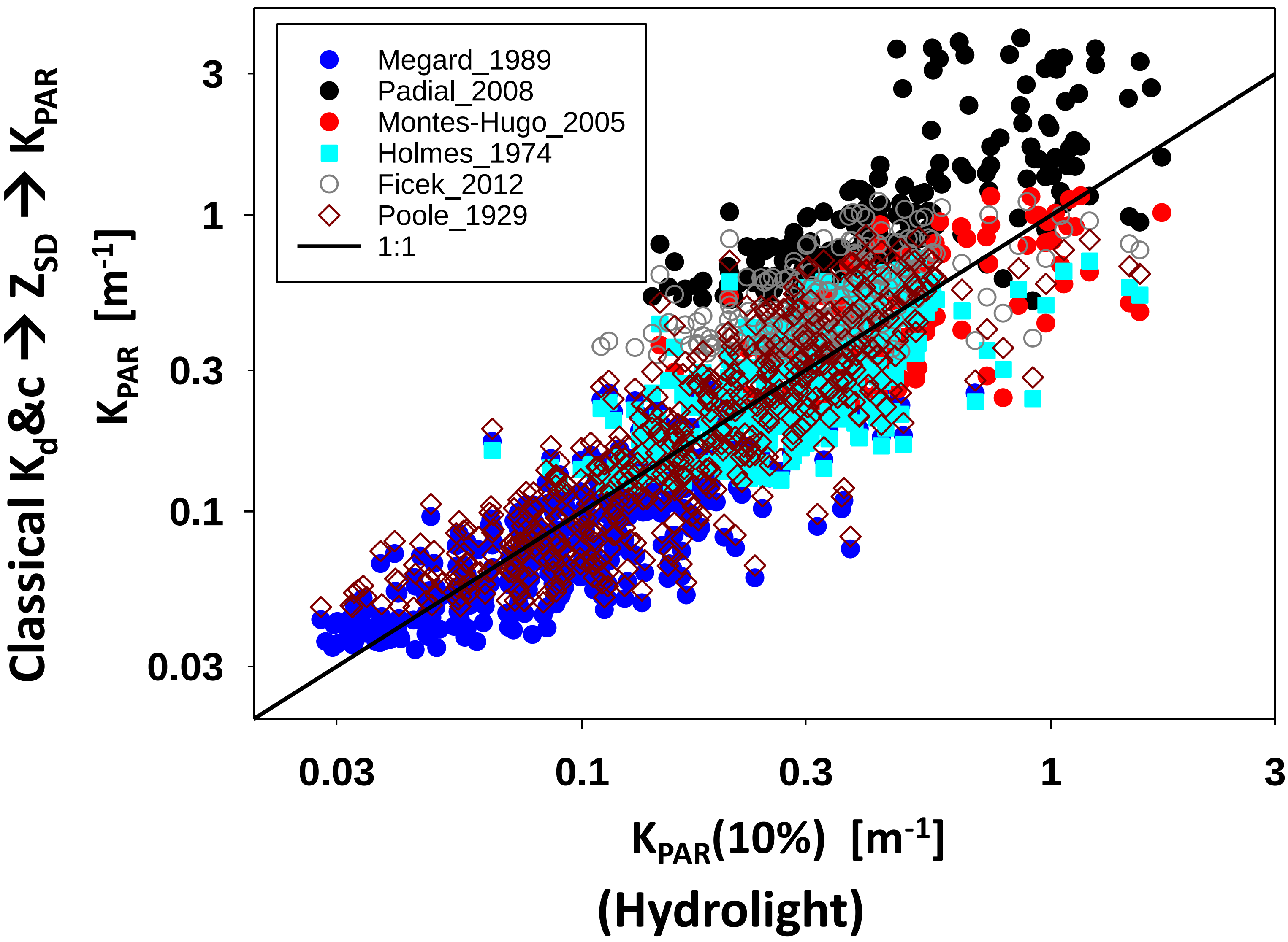
(Lee et al. 2018)

New Kd^tr → Z_{SD} → K_{PAR}



(Hydrolight)

(Lee et al. 2018)



(Lee et al. 2018)

For global "Case-1" waters (Boyce et al. 2012):

$$Chl = \frac{143.29}{(Z_{SD})^{2.08}}$$

Also for "Case-1" waters (Morel and Maritorena 2001):

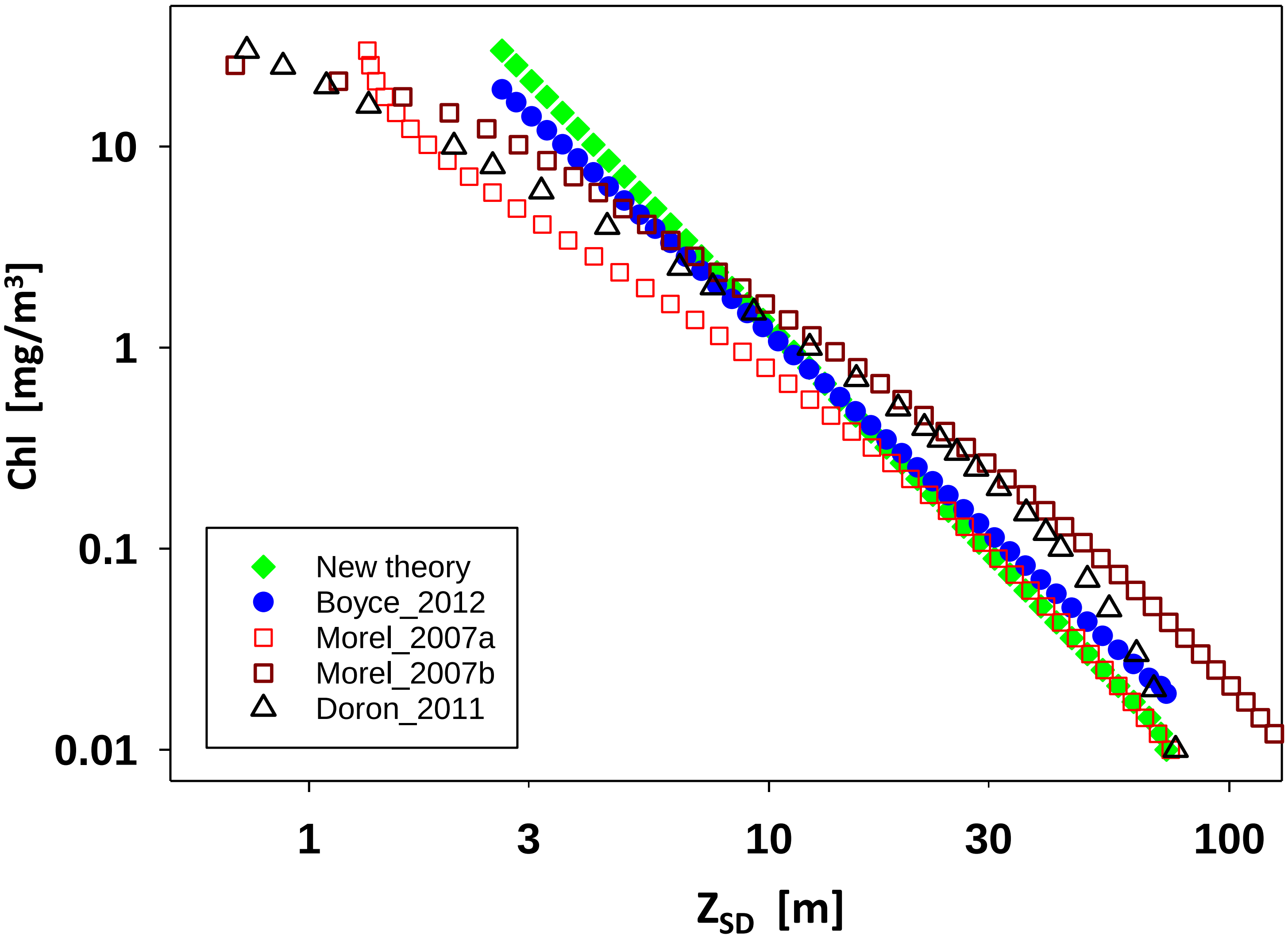
$$K_d(\lambda) = K_w(\lambda) + \chi(\lambda)(Chl)^{e(\lambda)}$$

↓

Z_{SD} vs Chl

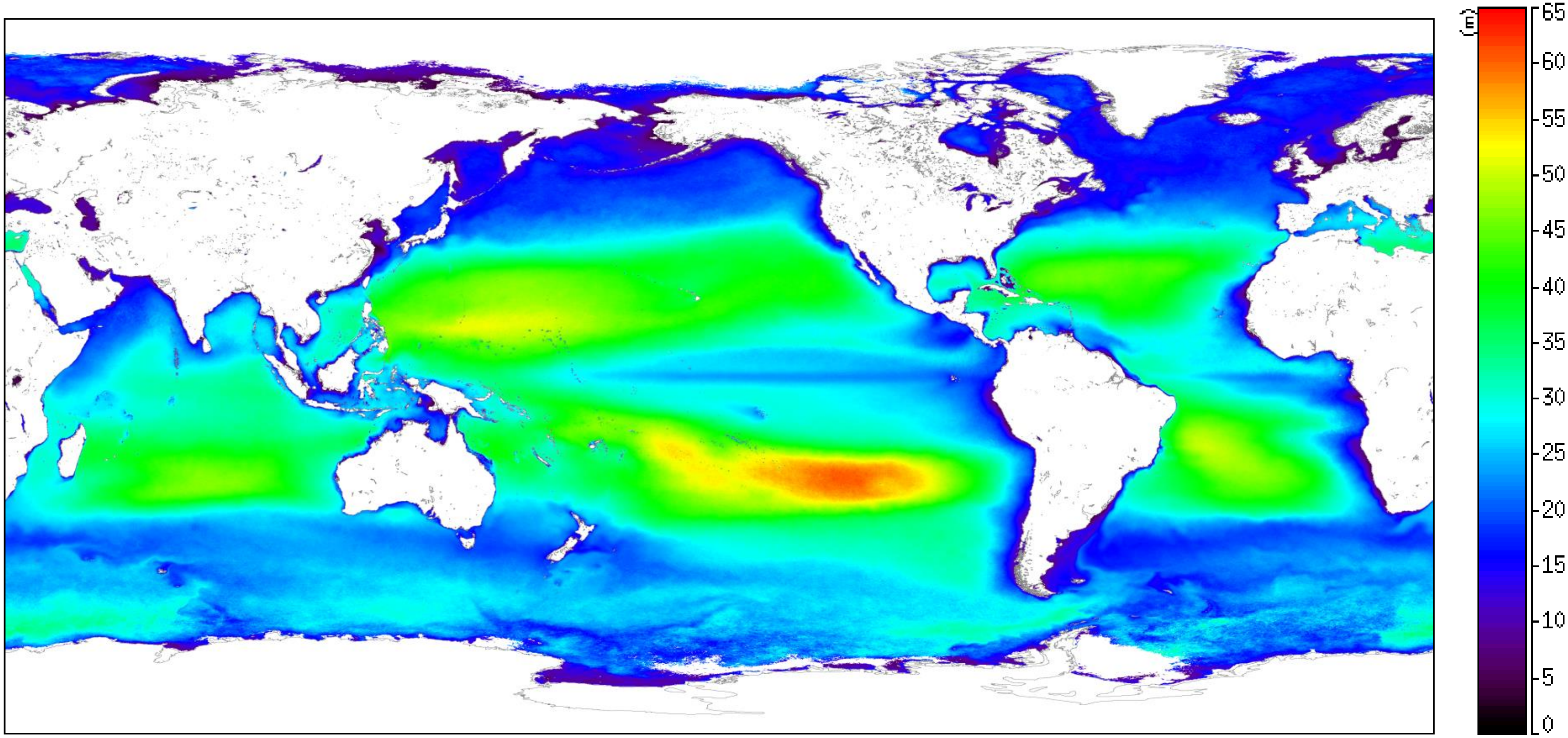
How consistent will the two be from Secchi theory?

Relationships between Z_{SD} and Chl:

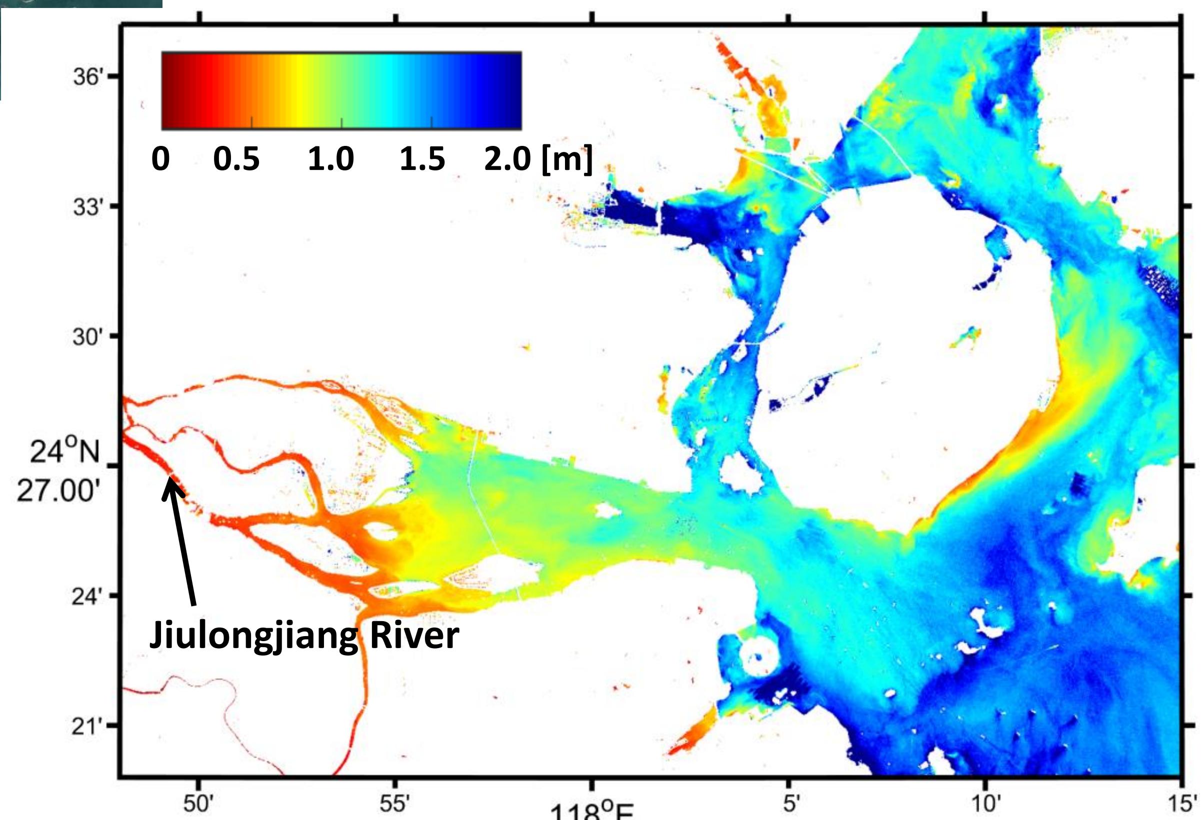


(Lee et al. 2018)

Global Z_{SD} from SeaWiFS



Application with Landsat-8 measurements



Why Secchi depth is not *c* dependent?

What does "seen"/"visible" mean?

C, O, E ⟷ Recognize/ differentiate

⟷ detection

Secchi Disk sighting → A detection

We don't care about the details; just want to know if it is there.

AĈS

PROFILER II

What can we do with Secchi depth measurement?

Z_{SD} → Chl, SPM, Trophic State index (TSI), fishery, …

$$Z_{eu} \approx 2.4\ Z_{SD}$$? ?

$$\text{IOPs} \rightarrow Z_{eu} \text{ and } Z_{SD}$$

↓

$$Z_{eu} \approx 3.5\ Z_{SD}$$

$$Z_{SD} \approx \frac{1}{K_d^{tr}}$$

$$\mathbf{Z_{SD}} \rightarrow K_d^{tr}$$

$$
\begin{cases}
R_{rs}(\lambda_1) = F(a_w(\lambda_1), a_{ph}(\lambda_1), a_{dg}(\lambda_1), b_{bw}(\lambda_1), b_{bp}(\lambda_1)) \\
R_{rs}(\lambda_2) = F(a_w(\lambda_2), a_{ph}(\lambda_2), a_{dg}(\lambda_2), b_{bw}(\lambda_2), b_{bp}(\lambda_2)) \\
\vdots \\
R_{rs}(\lambda_n) = F(a_w(\lambda_n), a_{ph}(\lambda_n), a_{dg}(\lambda_n), b_{bw}(\lambda_n), b_{bp}(\lambda_n))
\end{cases}
$$

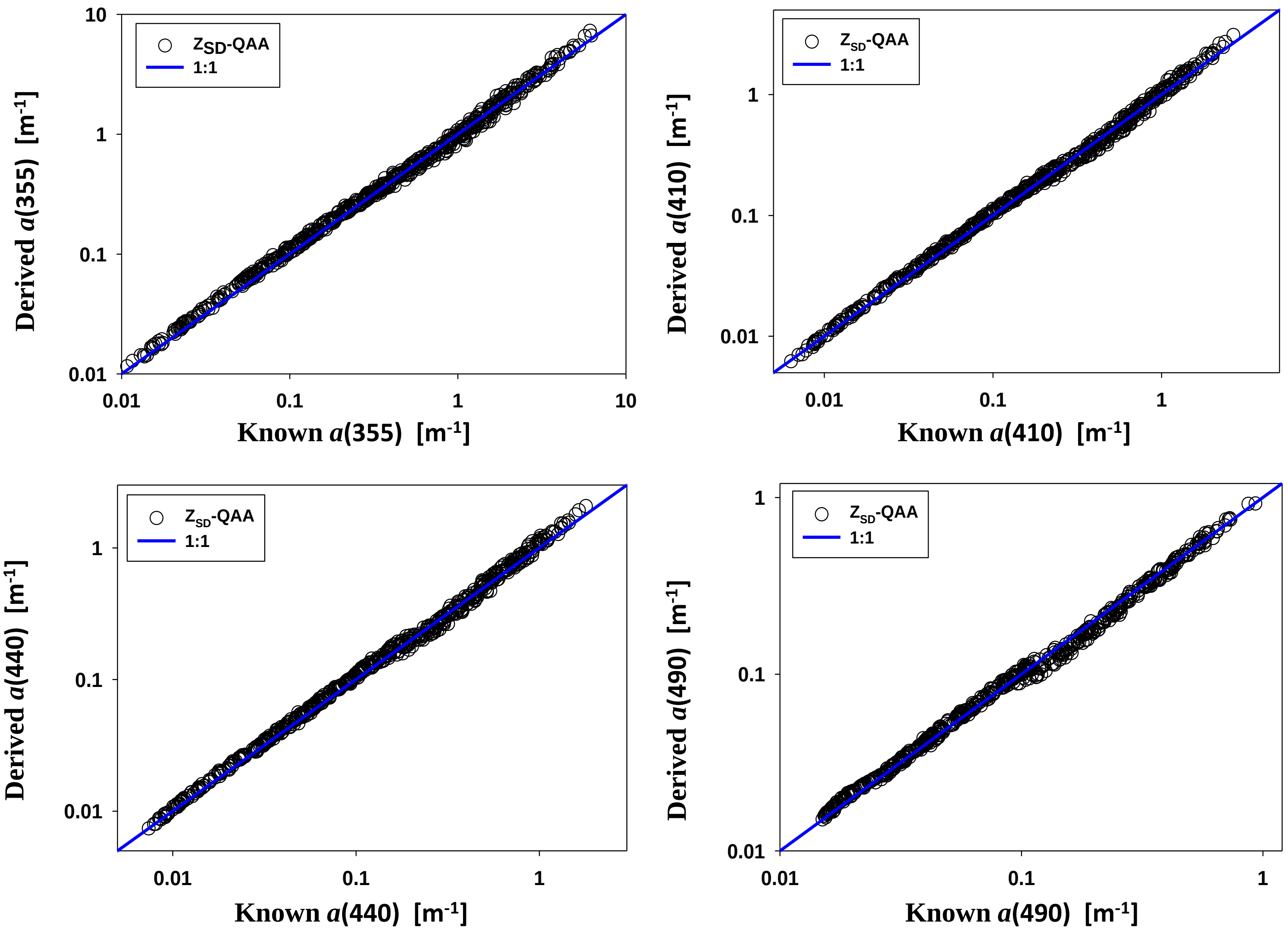
An ill formulated math problem!

$$\mathbf{Z_{SD}} \rightarrow K_d^{tr}$$

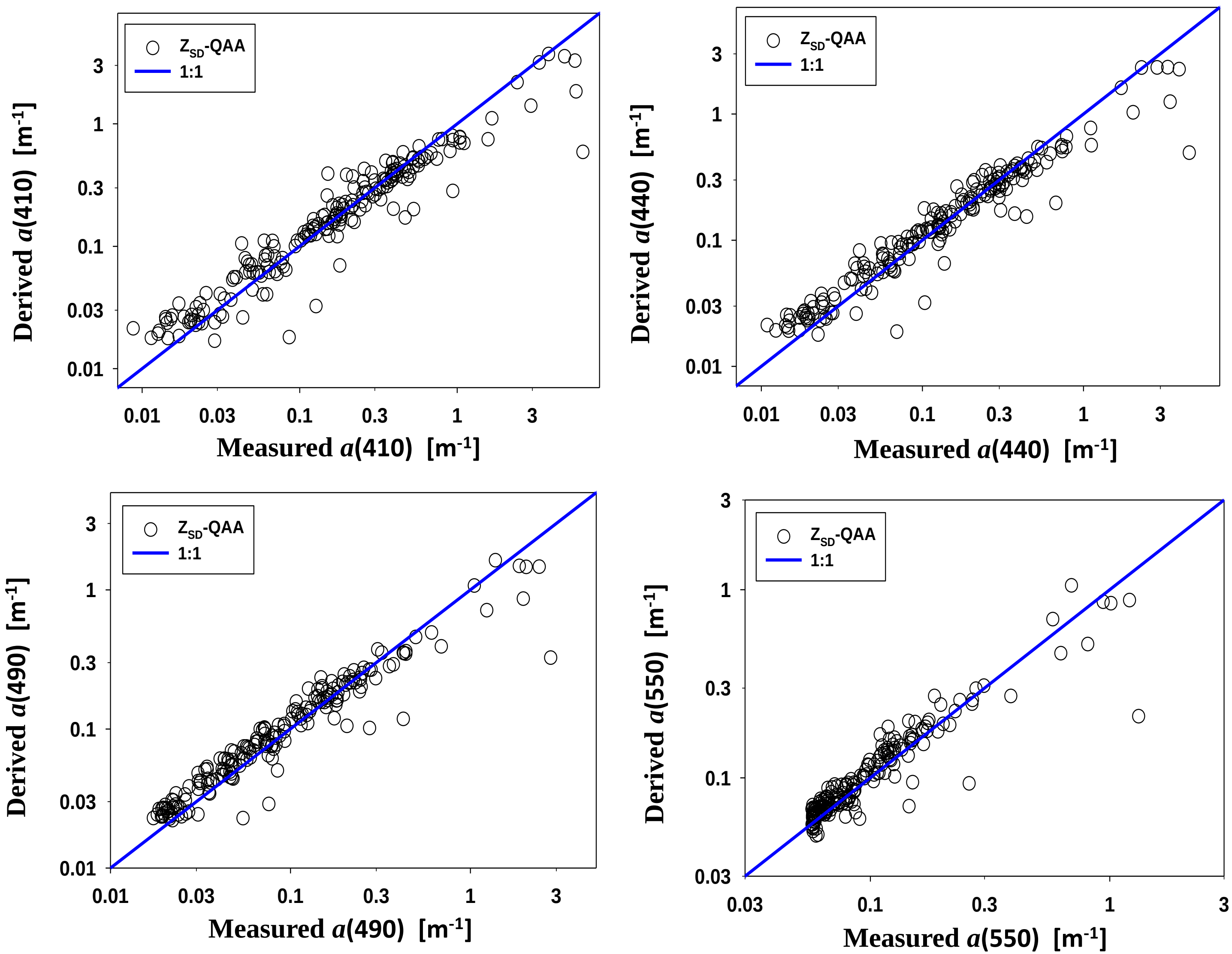
Provides independent measurement of water's optical property

➡ **Z_{SD}-QAA**

Results of Zsd-QAA: simulated data.



Results of Zsd-QAA: field data.

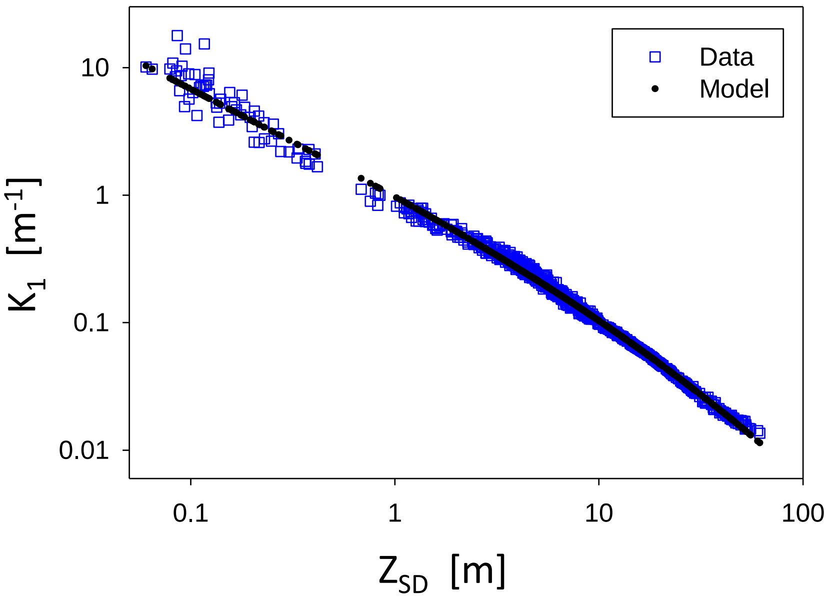


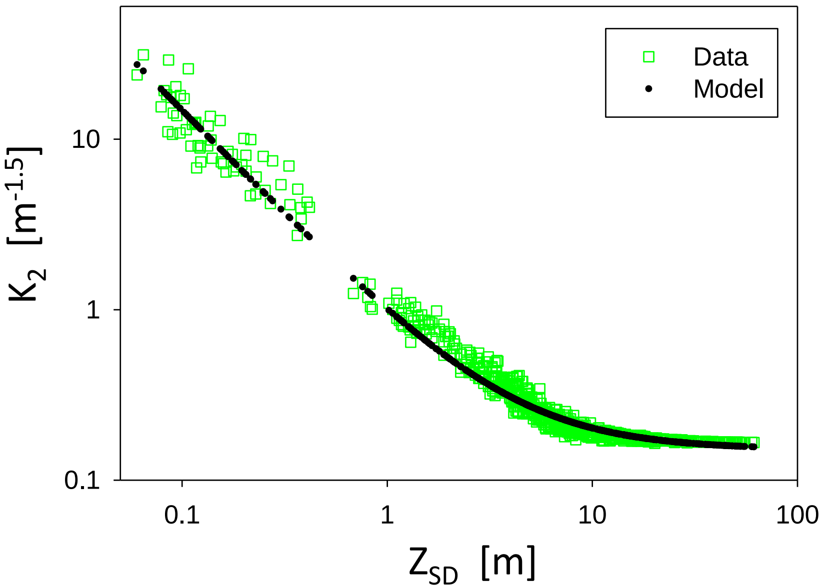
(Lee et al. 2018)

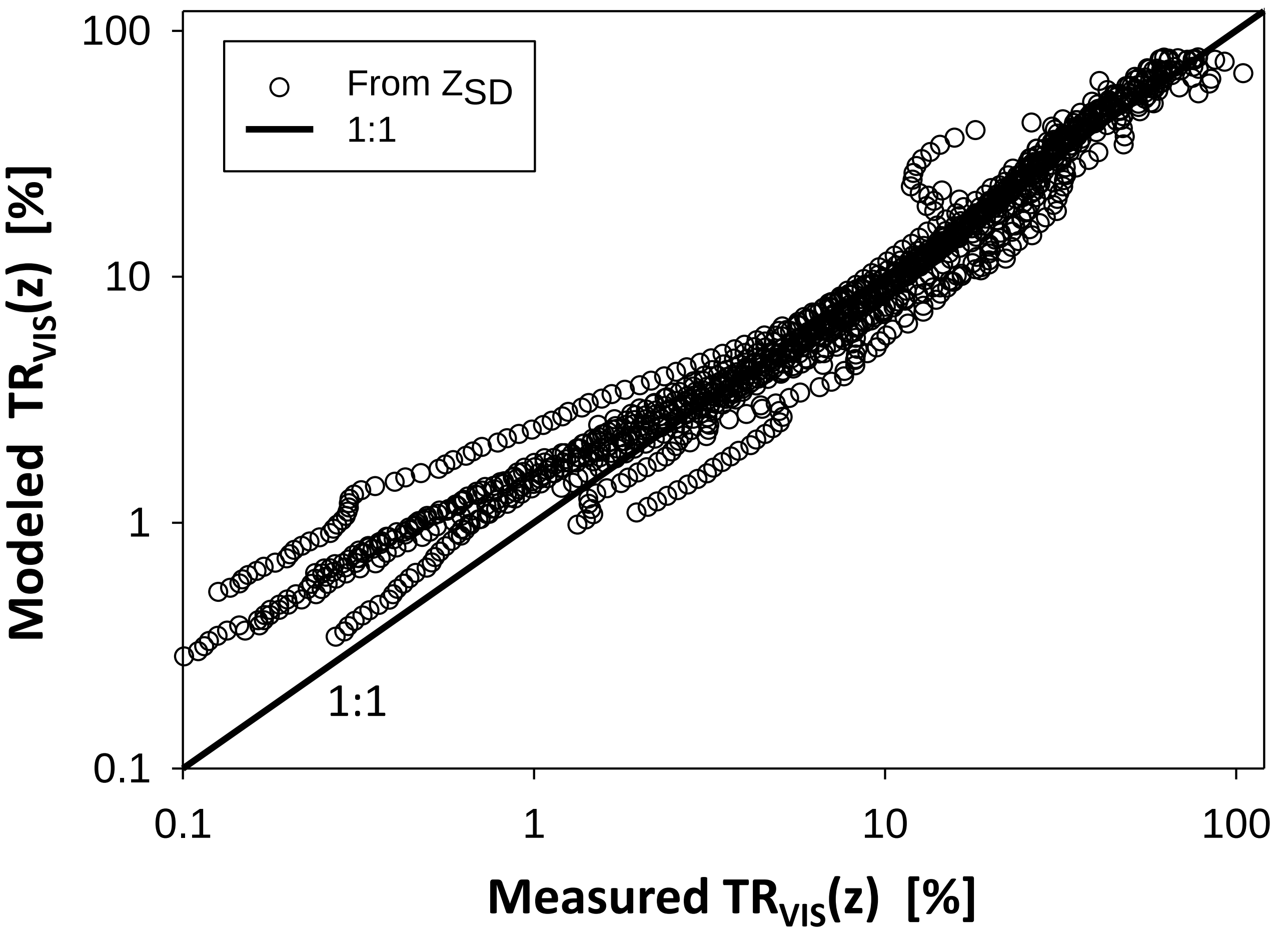
$$PAR(z) = PAR(0)\, e^{-K_{par}(z)\, z}$$

How to get PAR profiles for oceans of 100 years ago??

$$K_{PAR}(z) \approx K_1 + \frac{K_2}{(1+z)^{0.5}}$$


Data
Model
10
1
0.1
0.01
0.1
1
10
100
K_1 [m^{-1}]
Z_{SD} [m]


Data
Model
10
1
0.1
0.1
1
10
100
K_2 [$m^{-1.5}$]
Z_{SD} [m]



(Lee et al. 2018)

Summary:

New relationship for Z_{SD}:

$$Z_{SD} = \frac{1}{K_d^{tr} + K_L^{tr}} \ln\left(\frac{1}{C_t^r} \left(r_T - r_w^{tr} \right) \right)$$

Classical relationship for Z_{SD}:

$$Z_{SD} = \frac{1}{K_d + c} \ln\left(\frac{1}{C_t} \frac{r_T - r_w}{r_w} \right)$$

two key differences

1. attenuation: K_L^{tr} **vs** c

2. Evaluation of Contrast: $\left(r_T - r_w^{tr} \right)$ **vs** $\left(\frac{r_T - r_w}{r_w} \right)$

1. The century-old classical theory does not reflect the fact that a Secchi disk is *not* a point source for human eyes.

2. The contrast used in the classical theory is not consistent with the judgement decision of the eye-brain system.

3. The new under-water visibility theory overcomes both issues and provides plausible explanations for historical data and relationships.

4. The new theory opens the door to produce global Z_{SD} product from satellite water color remote sensing analytically.

5. Z_{SD} not only provides a direct/intuitive measurement of water's clarity that can bridge status of present day to 100 years ago, but also valuable for many other applications.

CLIMATE CHANGE Opinion

Global Water Clarity: Continuing a Century-Long Monitoring

An approach that combines field observations and satellite inferences of Secchi depth could transform how we assess water clarity across the globe and pinpoint key changes over the past century.

Secchi reading by Tim Plude on Wisconsin's Lake Tomahawk, October 2012. Credit: Laura Herman

By Zhongping Lee, Robert Arnone, Daniel Boyce, Bryan Franz, Steve Greb, Chuanmin Hu, Samantha Lavender, Marlon Lewis, Blake Schaeffer, Shaoling Shang, Menghua Wang, Marcel Wernand, and Cara Wilson 7 May 2018

Aquatic systems worldwide are changing because of increasing climate variability and human activities. Yet it is difficult to capture such changes without standardized long-term observations.

Water transparency or clarity is commonly represented as Secchi depth (Z_{SD}) measured with a Secchi disk. Secchi depth is determined by lowering the disk into the water and recording the depth where it is no longer visible to an observer at the surface.

The measurement provides a first-order indicator of water quality and ecosystem health. Unlike