GOCAD and the Remote Sensing of Dissolved Organic Carbon and CDOM in the Global Ocean.

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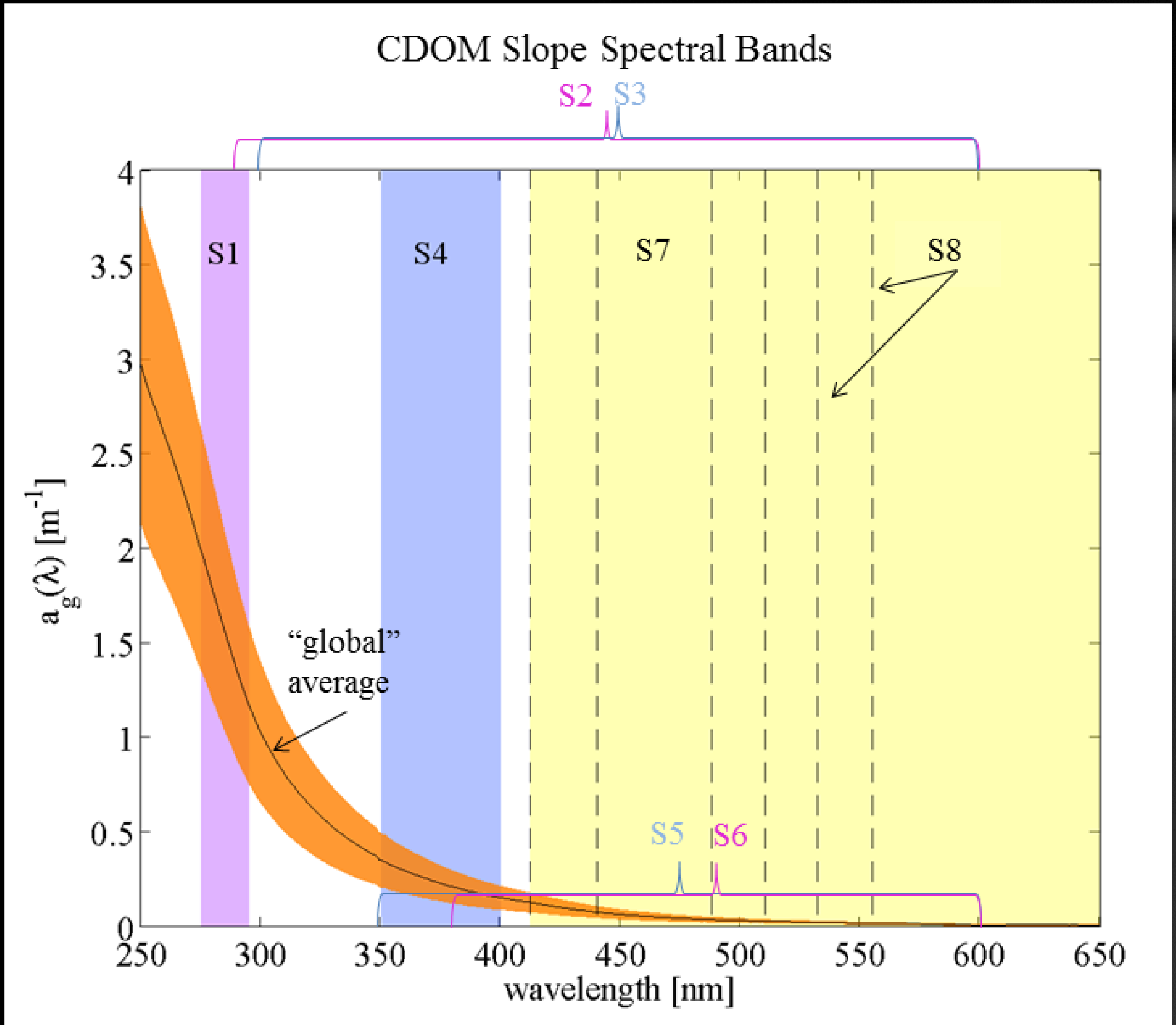
DOC and Climate

- S. Arrhenius 1896: CO_2 from fossil fuel burning leads to greenhouse effect
- Siegenthaler and Sarmiento 1993: DOC comprises vast majority of marine organic carbon ~equivalent to atmospheric CO_2 pool
- Hedges 2002: Oxidation of just 1% of DOC would generate a flux of CO_2 into the atmosphere equal to all fossil fuel burned in a year
- Belanger et al. 2006: Photoproduction of CO_2 through oxidation of CDOM increased ~15% in the Arctic recent years due to the decrease in sea ice

DOC and Ocean Color; CDOM

$$a_g(\lambda) = a_g(\lambda_0)\exp\left(-S_g(\lambda - \lambda_0)\right)$$



Spectral slopes reflect age, molecular weight, origin, photooxidation, etc.

NOMAD and the synthetic IOCCG datasets have been extremely useful to algorithm development, but for our purposes, a carbon-centric, ocean color database is required which extends into the UV, includes larger numbers of field stations (~40X more), and matches CDOM & DOC to satellite imagery as well as in situ radiometry.

Global Ocean Carbon Algorithm Database
GOCAD

GOCAD

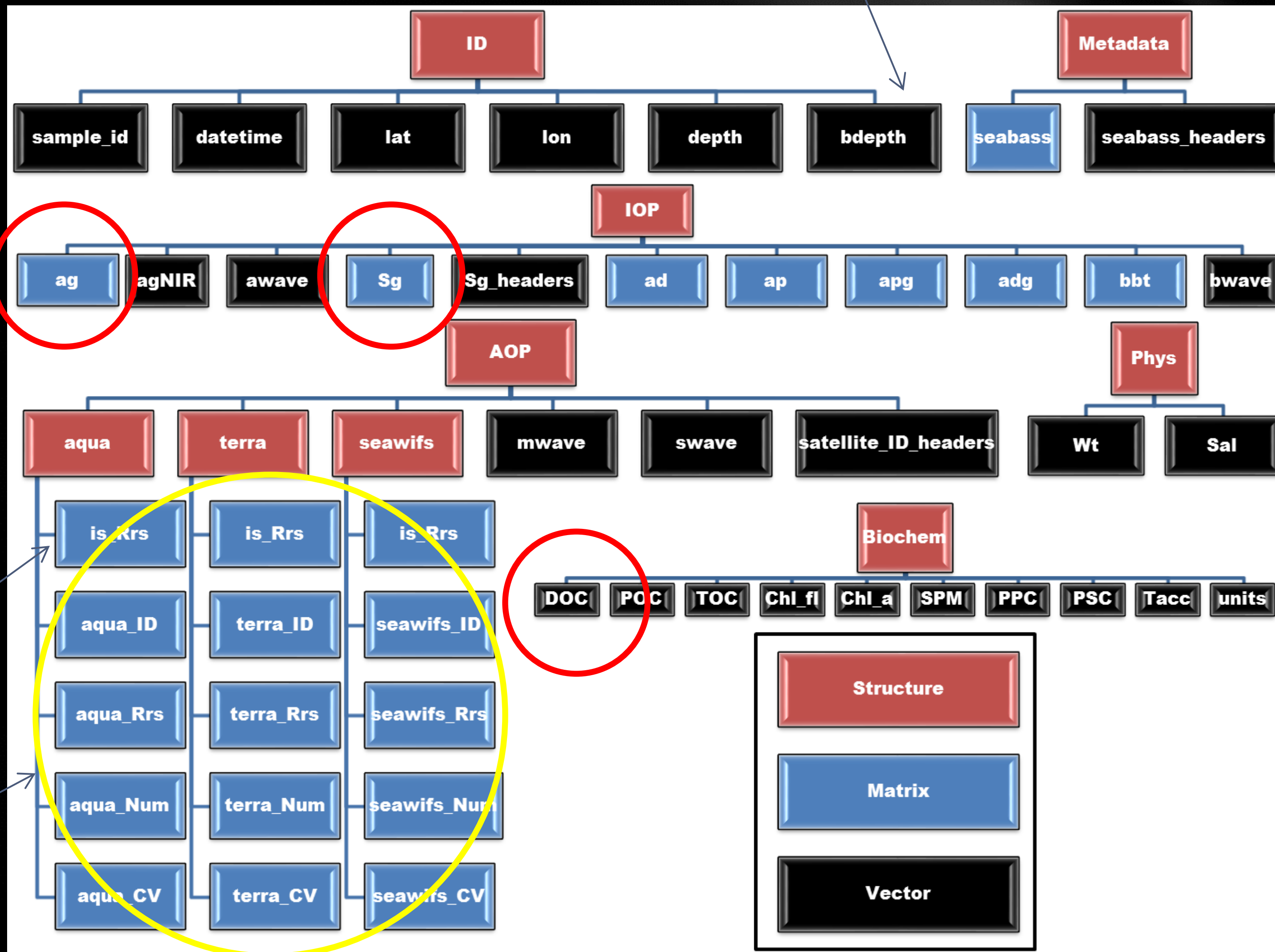
GEBCO 08 0.05

SeaBASS
Hansell/Carlson

5-10 m surface average, 1 km gridded, hyperspectral, Bailey & Werdell 2006 (5x5, 8 hrs, etc.)

RSR-weighted

OBPG L2



Rigorously quality controlled!

Table 2. Summary of field data collection campaigns.

Experiment	Principal Investigators	Cruises	Numbers of Stations: CDOM	CDOM & IS*	CDOM & SAT**	DOC	DOC & IS*	DOC & SAT**	Min. Lat	Max. Lat	Min. Lon	Max. Lon	Year(s)
Catlin Arctic Survey	V. Hill	1	8	0	0	0	0	0	78.771	78.771	-104.721	-104.721	2011
AMT	W. Balch	5	23211	7703	1918	0	0	0	-47.27	49.716	-55.455	18.611	2005-2011
Gulf of Maine	W. Balch	33	8077	0	3251	0	0	0	42.683	44.058	-70.267	-66.172	2005-2008
Scotia Prince Ferry	W. Balch	47	11521	51	8397	0	0	0	43.604	43.798	-70.026	-66.164	2001-2004
2009oct Chesapeake	W.J. Rhea	1	13	10	4	0	0	0	38.136	39.062	-76.448	-76.229	2009
Totals		535	48574	8857	14568	1957	255	302	-70.999	78.771	-177.99	179.545	1984-2012

CV1	A. Mannin
CV2	A. Mannin
CV3	A. Mannin
CV4	A. Mannin
CV5	A. Mannin
CV6	A. Mannin
D01	A. Mannin
D02	A. Mannin
D03	A. Mannin
D04	A. Mannin
OCV1	A. Mannin
OCV2	A. Mannin
OCV3	A. Mannin
OCV5	A. Mannin
PL6	A. Mannin
GOMECC	A. Mannin
GEO-CAPE	A. Mannin Mulhollan
MONTEREY BAY	B. Arnone
WOCE P14S P15S	B. Tilbroo
Carbon Transport MS R.	C. Del Ca:
GasEx	C. Del Ca:
Big Bend	C. Hu
GEO-CAPE CBODAQ	C. Hu
GOM Oil Spill	C. Hu

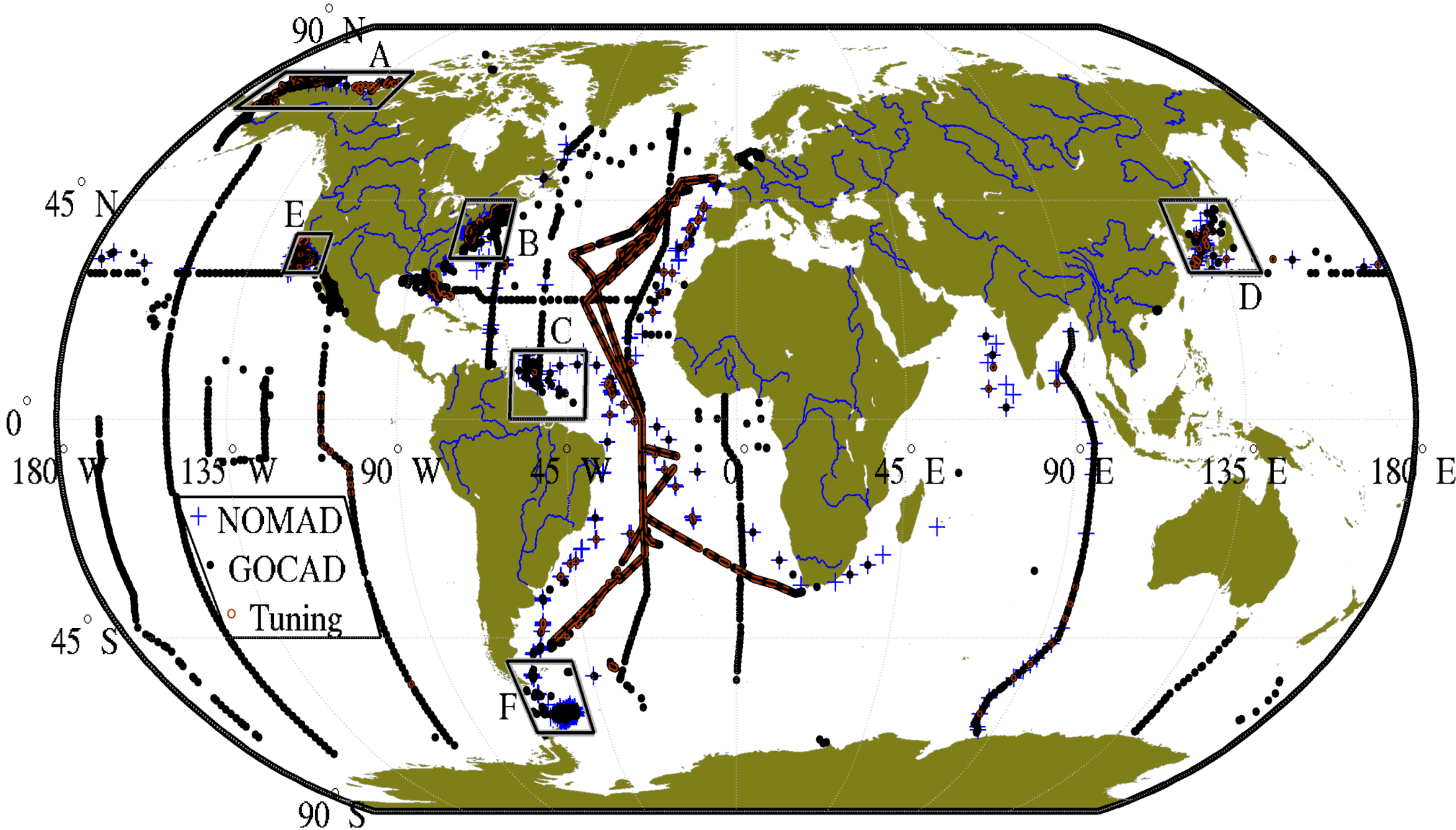
PenBaySurvey	C. Roesler
San Diego Coastal Project	D. Stramski, M. Stramska
NASA Gulf of Maine	D. Phinney, D. Pl J. Brown
NOAA Gulf of Maine	D. Phinney, D. Pl J. Brown
Panama City Florida	D. Phinney, D. Pl J. Brown
Plumes and Blooms	D. Siegel
CLIVAR A13.5 2010	D. Hansell
CLIVAR I05 2009	D. Hansell
CLIVAR I08S 2007	D. Hansell
CLIVAR P02 2004	D. Hansell
CLIVAR P16N 2006	D. Hansell
CLIVAR P16S 2005	D. Hansell
CLIVAR P18 2007	D. Hansell
HLY-02-01	D. Hansell
HLY-02-03	D. Hansell
HLY-0403	D. Hansell
SR03	D. Hansell
WOCE AR01 A05	D. Hansell
ACE-ASIA	G. Mitchell, M. K
AMLR	G. Mitchell, M. K
Aerosols Index	G. Mitchell, M. K
CALCOFI	G. Mitchell, M. K
Sea_of_Japan	G. Mitchell, M. K
Arc00	G. Cota

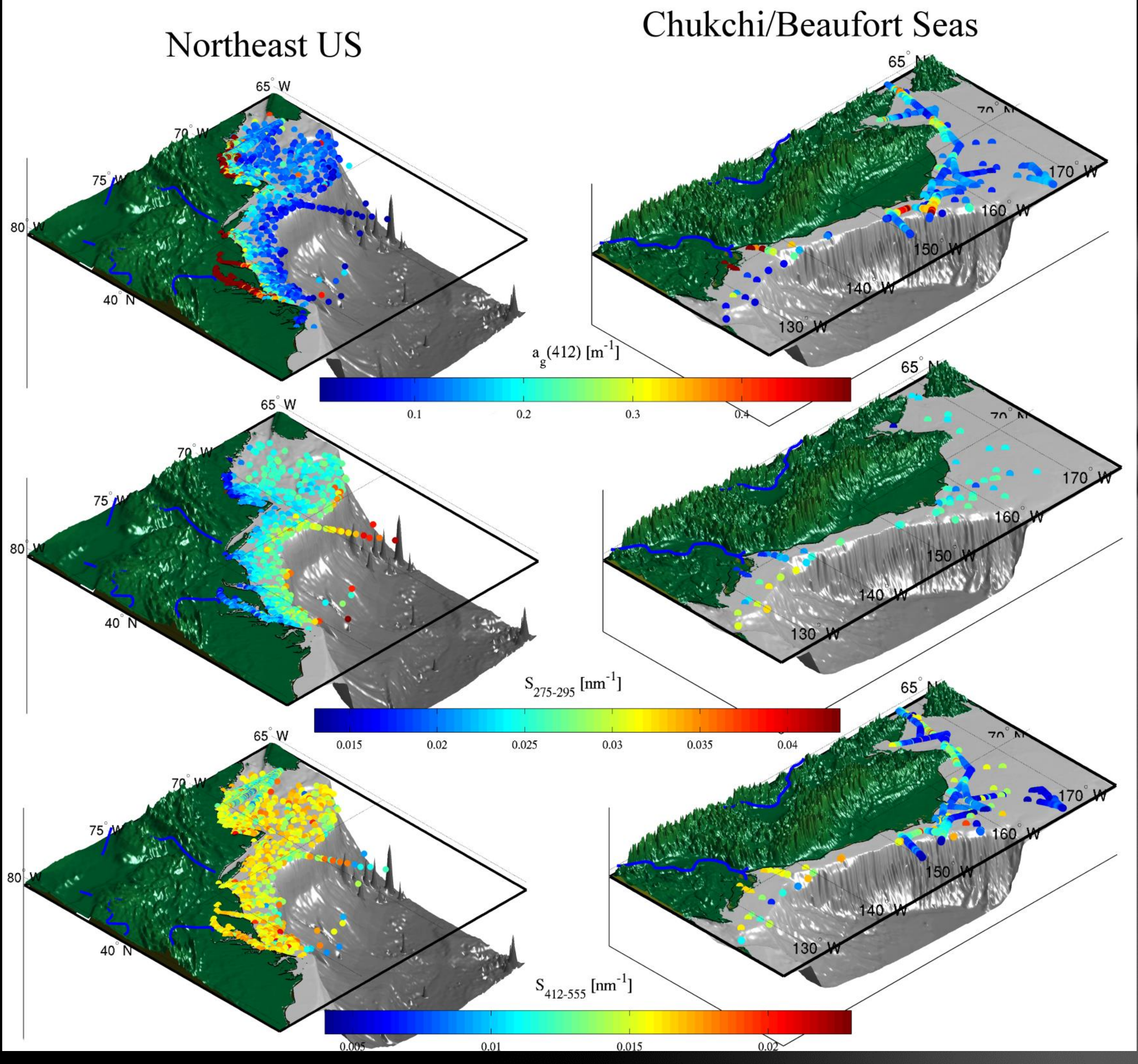
NSF-BWZ	G. Mitchell	2
Benthic Ecol. from Space	H. Dierssen, R. Zimmerman	4
Kieber Photochemistry 03	H. Sosik	1
MVCO	H. Sosik	34
GOCAL	J.R.V Zaneveld, W.S. Pegau	6
PREPP	J. Chen	5
SAB Mapping	J. Nelson, A. Subramaniam	2
GEOTRACES	J. Chaves	1
COOA	J. Salisbury, D. Vandemark, C. Hunt	3
NOAA CSC	J. Brock, A. Subramanian, K. Waters	1
BOA	K. Carder	1
EcoHAB	K. Carder	19
Okeechobee	K. Carder	1
Redtide	K. Carder	2
TOTO	K. Carder	3
ACE-INC	L.W. Harding_Jr.,M. Mallonee, A. Magnuson	6
BIOCOMPLEXITY	L.W. Harding_Jr.,M. Mallonee, A. Magnuson	11

Ocean Color Cal Val	M.S. Twardowski, A.H. Barnard, J.R.V. Zaneveld	1	14	13
Tokyo Bay	M. Kishino	1	1	0
Global_CDOM	N. Nelson, D. Siegel	2	19	0
CLIVAR	N. Nelson, D. Siegel, C. Carlson	9	80	17
TAO 2005	N. Nelson, D. Siegel, C. Carlson	1	61	0
TAO 2006	N. Nelson, D. Siegel, C. Carlson	2	78	0
BBOP	N. Nelson, D. Siegel	116	78	7
Active Fluorescence 2001	R. Morrison, H. Sosik	1	4	0
Kieber Photochemistry 02	R. Morrison, H. Sosik	1	69	0
GLOBEC	R. Morrison, H. Sosik	5	23	0
FRONT	R. Morrison, H. Sosik	3	9	0
CLIVAR A16N 2003	R. Freely	1	0	0
CLIVAR A16S 2005	R. Freely	1	0	0
CLIVAR A20 2003	R. Freely	1	0	0
CLIVAR A22 2003	R. Freely	1	0	0
CLIVAR I09N 2007	R. Freely	1	0	0
North Carolina 2005	R. Stumpf, P. Tester	5	32	4
North Carolina 2006	R. Stumpf, P. Tester	2	12	0
Chesapeake Light Tower	R. Zimmerman, G. Cota	3	71	59
North Sea	R. Doerffer	1	32	0

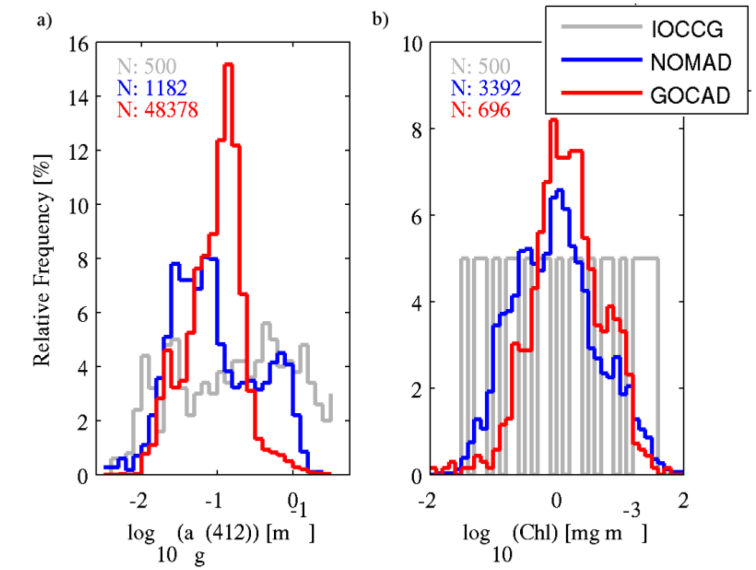
* IS is *in situ* $Rrs(\lambda)$, **SAT is satellite $Rrs(\lambda)$

Field Stations with CDOM and/or DOC

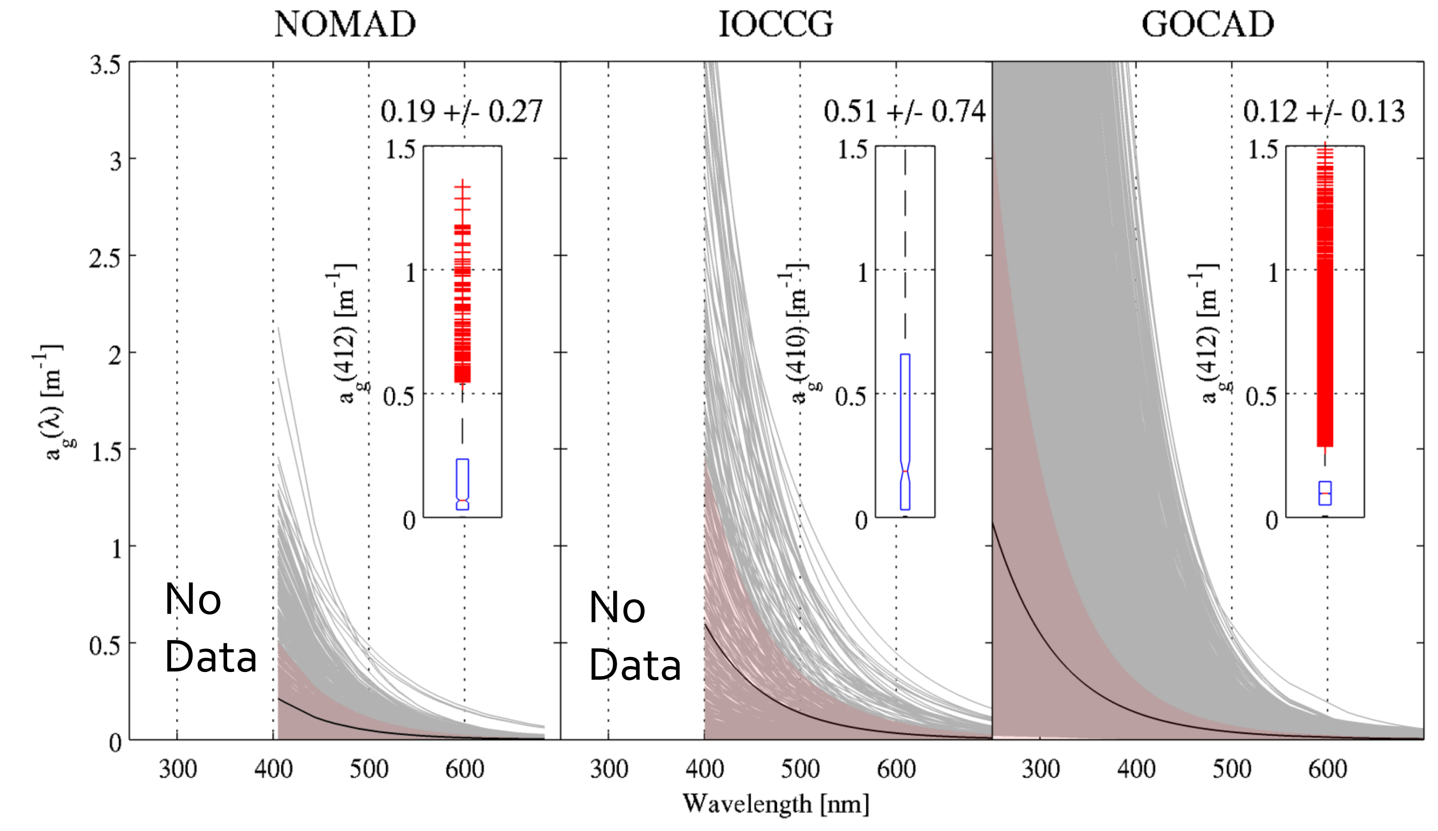




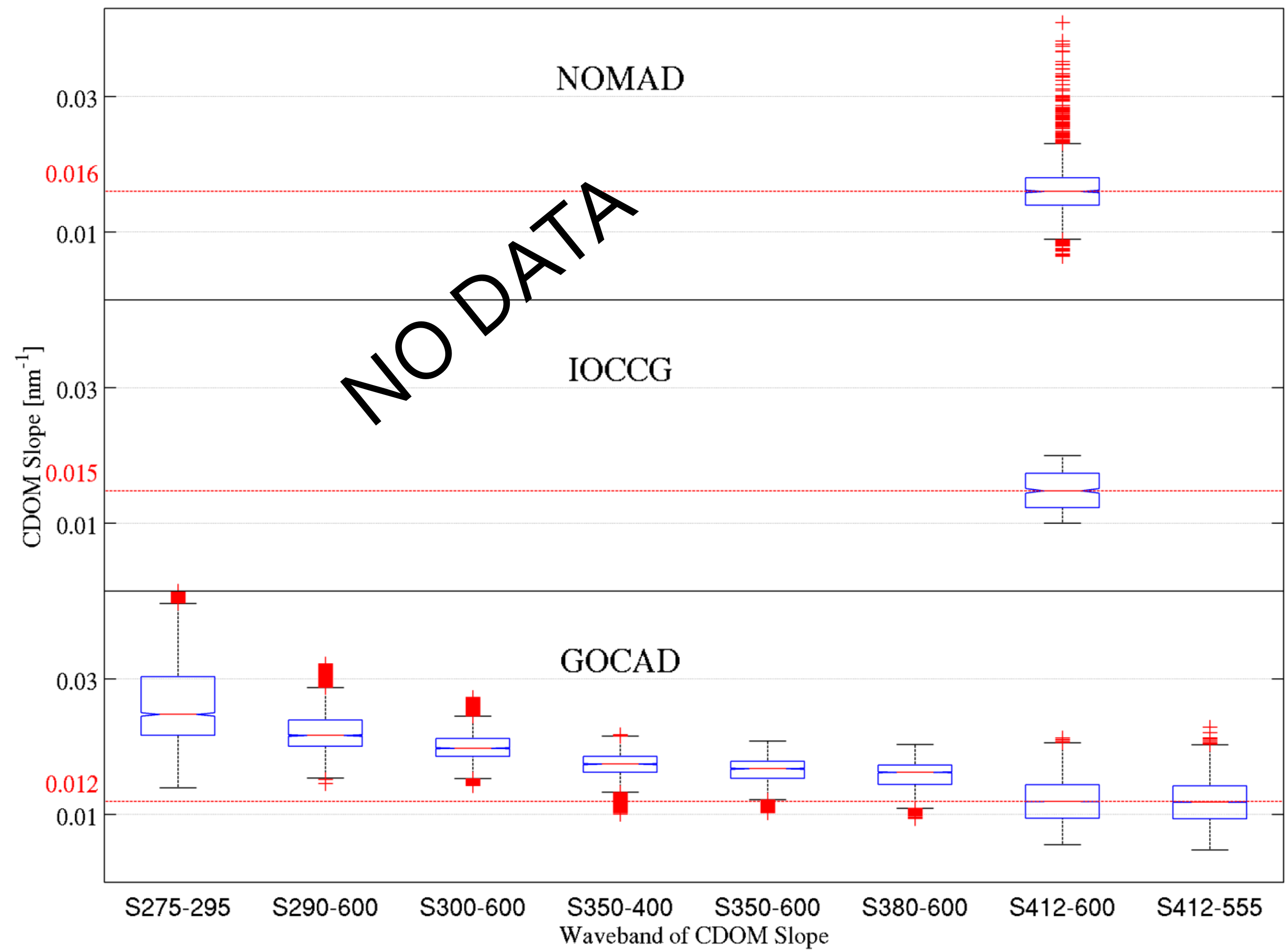
Northeast US
Chukchi/Beaufort Seas
65° W
70° W
75° W
80° W
40° N
65° N
70° N
170° W
160° W
150° W
140° W
130° W
$a_g(412)$ [m^{-1}]
0.1
0.2
0.3
0.4
$S_{275-295}$ [nm^{-1}]
0.015
0.02
0.025
0.03
0.035
0.04
$S_{412-555}$ [nm^{-1}]
0.005
0.01
0.015
0.02

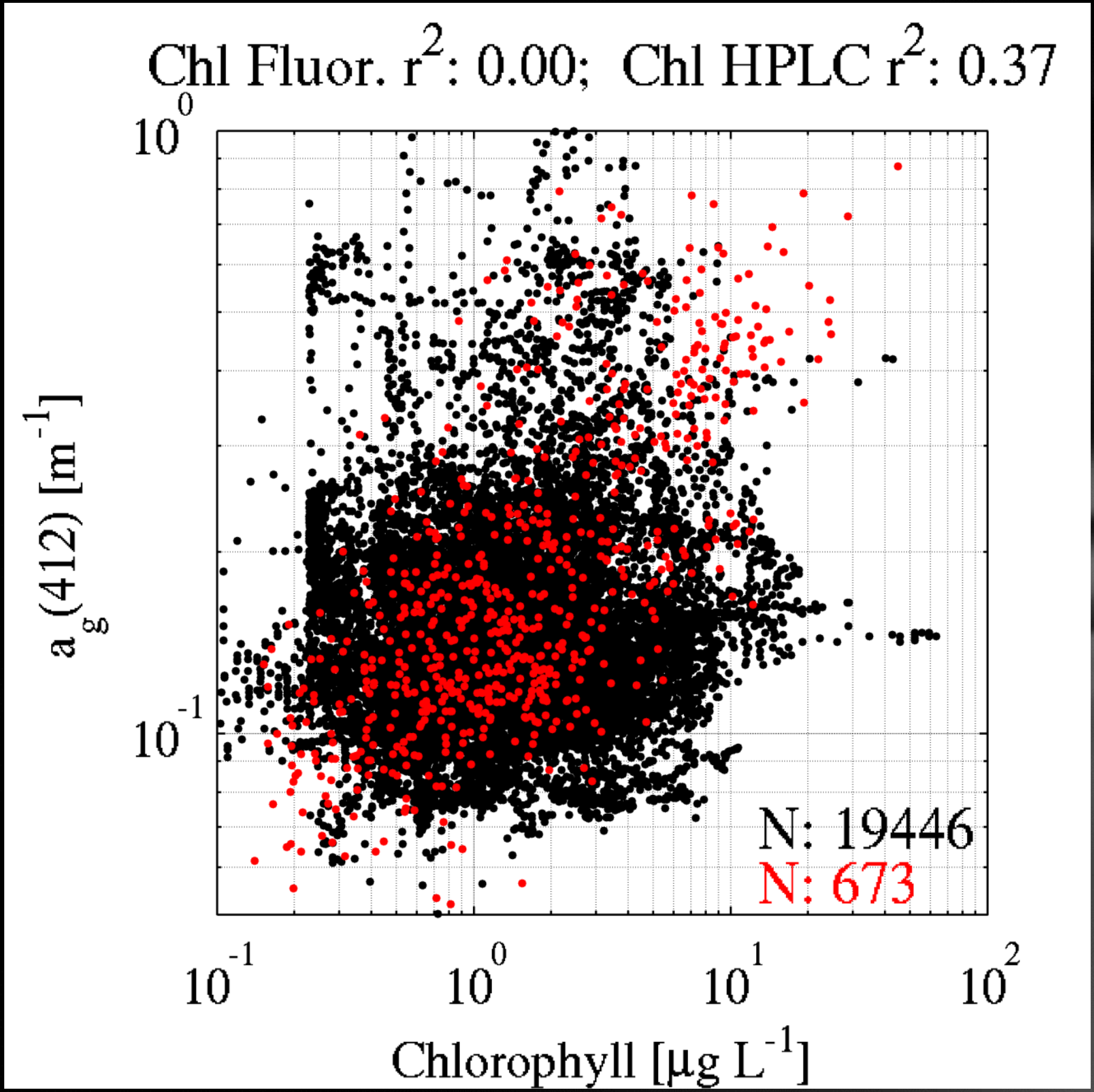


a)
b)
IOCCG
NOMAD
GOCAD
N: 500
N: 1182
N: 48378
N: 500
N: 3392
N: 696
Relative Frequency [%]
log10(ag(412)) [m-1]
log10(Chl) [mg m-3]



NOMAD
IOCCG
GOCAD
0.19 +/- 0.27
0.51 +/- 0.74
0.12 +/- 0.13
ag(412) [m-1]
ag(410) [m-1]
ag(412) [m-1]
ag(λ) [m-1]
No Data
No Data
Wavelength [nm]

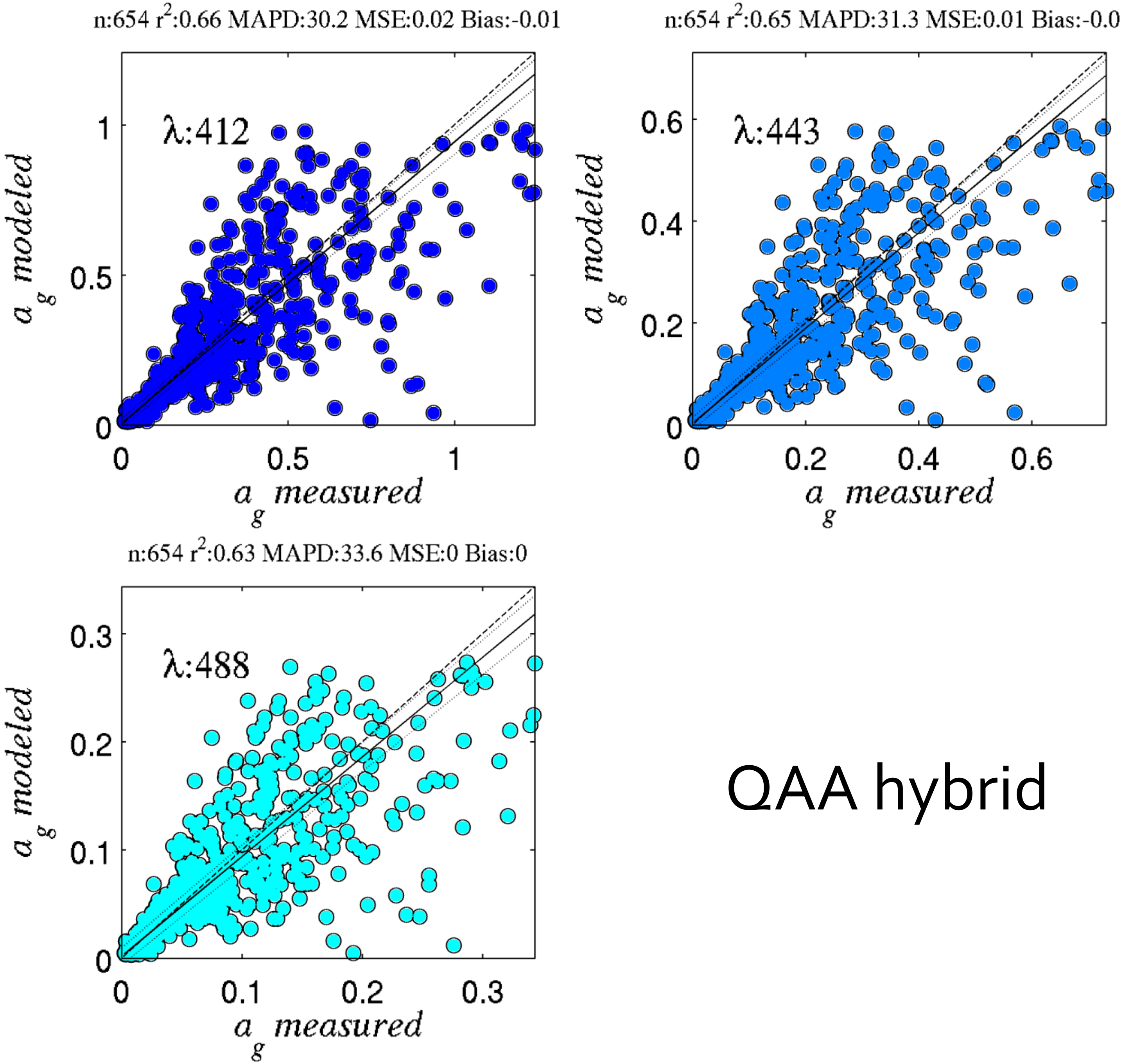

NOMAD
IOCCG
GOCAD
NO DATA
0.03
0.016
0.01
0.03
0.015
0.01
0.03
0.012
0.01
CDOM Slope [nm-1]
S275-295
S290-600
S300-600
S350-400
S350-600
S380-600
S412-600
S412-555
Waveband of CDOM Slope



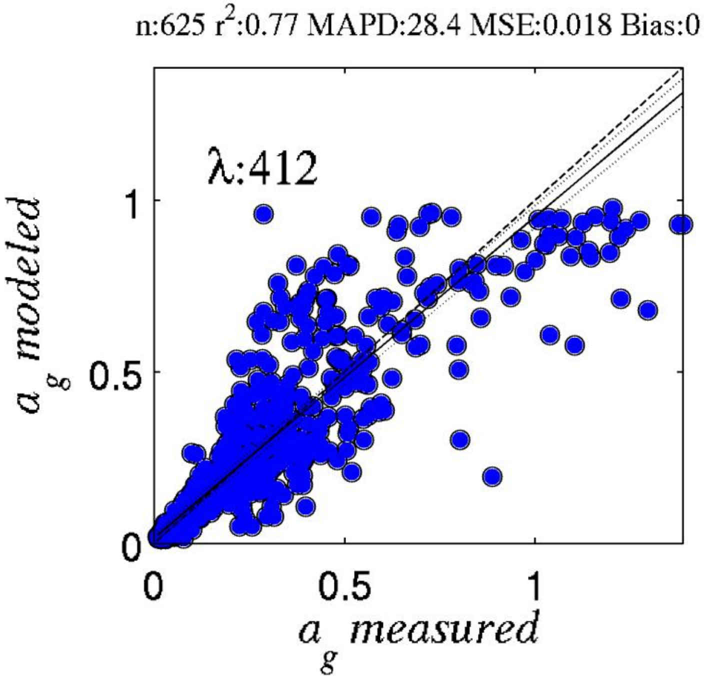
What/where *are* Case 1 waters, anyway?

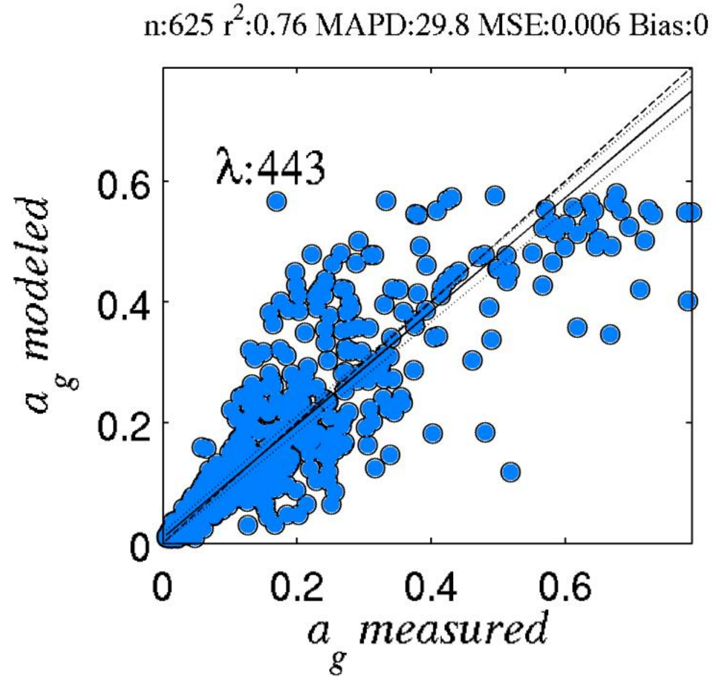
Algorithm Development

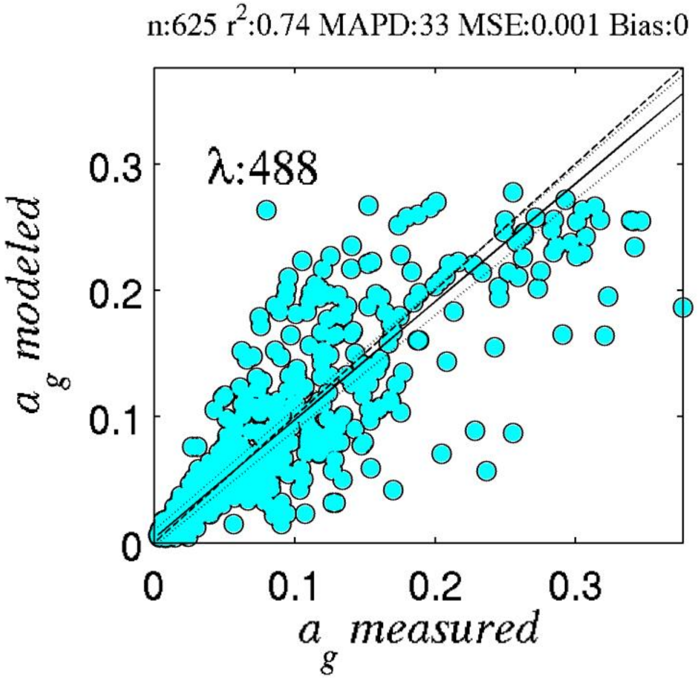
- Empirical Approaches
  - Band ratio, one-phase exponential decay model (EXP)
  - Multiple Linear Regression (MLR)
  - Machine Learning
    - Random Forest Tree-Bagger (RFTB)
- Semi-analytical Approaches (*Hybridized here for CDOM, not CDM, but no UV, and no DOC)
  - Quasianalytical Algorithm (QAA)
  - Generalized Inherent Optical Property (GIOP)
  - *CDM is related to a_g (CDOM) and b_{bp} (NAP)
- All algorithms were tuned/optimized/trained on *in situ* reflectances and validated on satellite data from independent field stations.


n:654 r2:0.66 MAPD:30.2 MSE:0.02 Bias:-0.01
λ:412
a g modeled
a g measured
n:654 r2:0.65 MAPD:31.3 MSE:0.01 Bias:-0.01
λ:443
a g modeled
a g measured
n:654 r2:0.63 MAPD:33.6 MSE:0 Bias:0
λ:488
a g modeled
a g measured

QAA hybrid

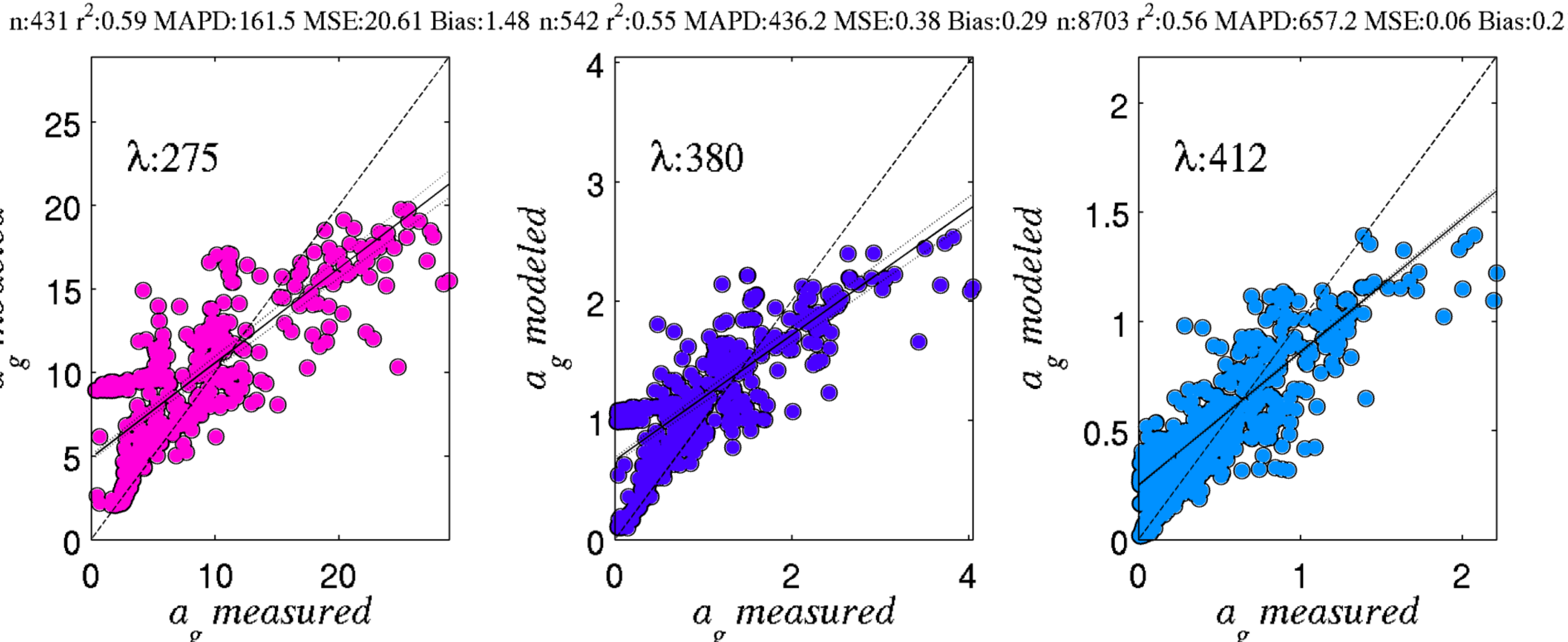

n:625 r2:0.77 MAPD:28.4 MSE:0.018 Bias:0
λ:412
a g modeled
a g measured
0
0.5
1


n:625 r2:0.76 MAPD:29.8 MSE:0.006 Bias:0
λ:443
a g modeled
a g measured
0
0.2
0.4
0.6

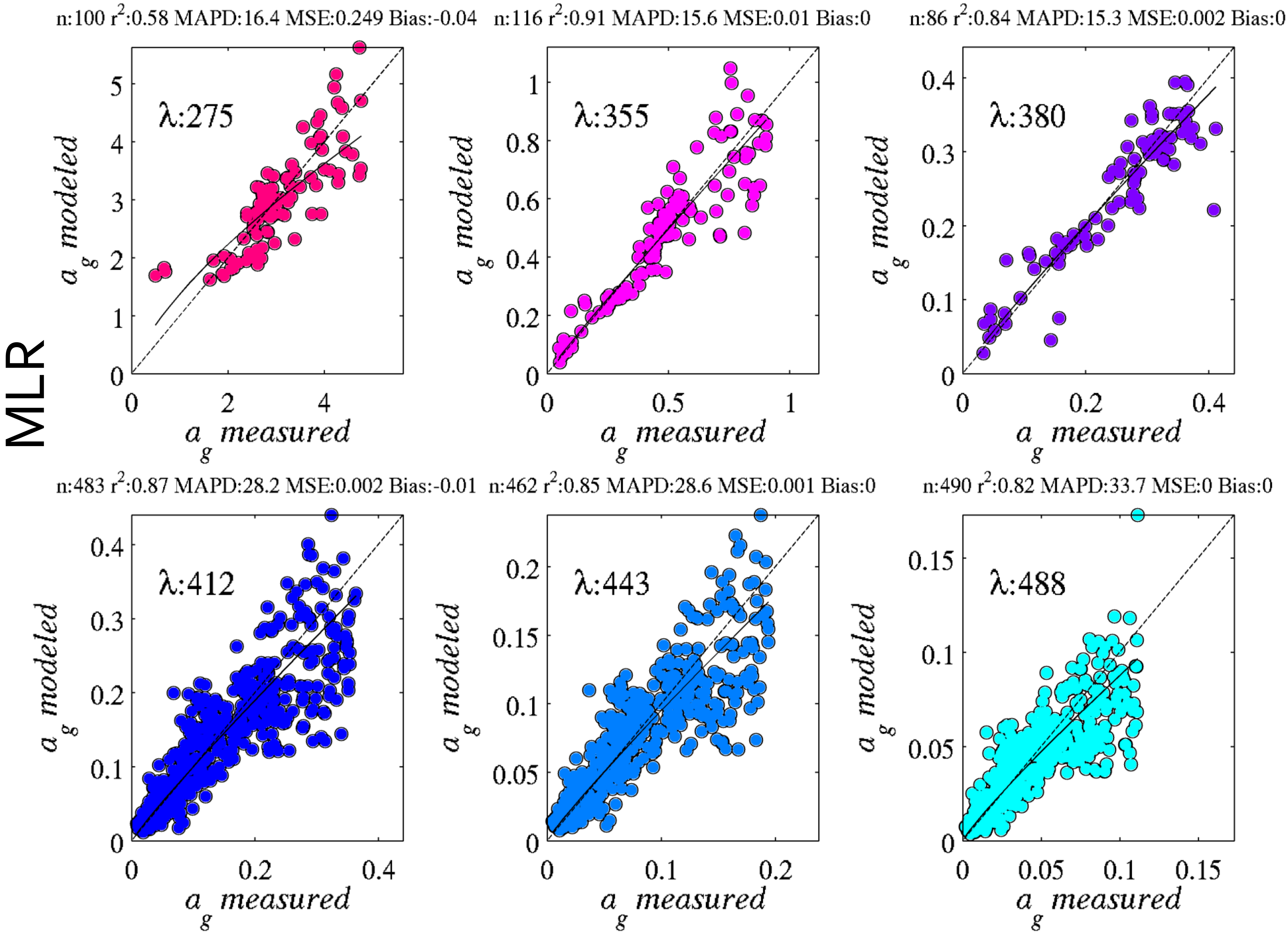

n:625 r2:0.74 MAPD:33 MSE:0.001 Bias:0
λ:488
a g modeled
a g measured
0
0.1
0.2
0.3

GIOP hybrid

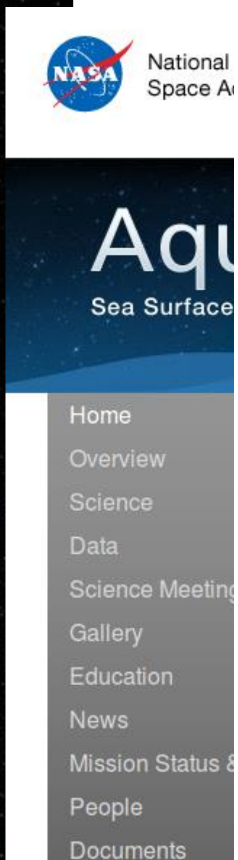
RFTB



n:431 r²:0.59 MAPD:161.5 MSE:20.61 Bias:1.48
n:542 r²:0.55 MAPD:436.2 MSE:0.38 Bias:0.29
n:8703 r²:0.56 MAPD:657.2 MSE:0.06 Bias:0.21
λ:275
λ:380
λ:412
a g modeled
a g measured
0
5
10
15
20
25
0
10
20
0
1
2
3
4
0
2
4
0
0.5
1
1.5
2
0
1
2


MLR
n:100 r2:0.58 MAPD:16.4 MSE:0.249 Bias:-0.04
λ:275
n:116 r2:0.91 MAPD:15.6 MSE:0.01 Bias:0
λ:355
n:86 r2:0.84 MAPD:15.3 MSE:0.002 Bias:0
λ:380
n:483 r2:0.87 MAPD:28.2 MSE:0.002 Bias:-0.01
λ:412
n:462 r2:0.85 MAPD:28.6 MSE:0.001 Bias:0
λ:443
n:490 r2:0.82 MAPD:33.7 MSE:0 Bias:0
λ:488
a g modeled
a g measured

What



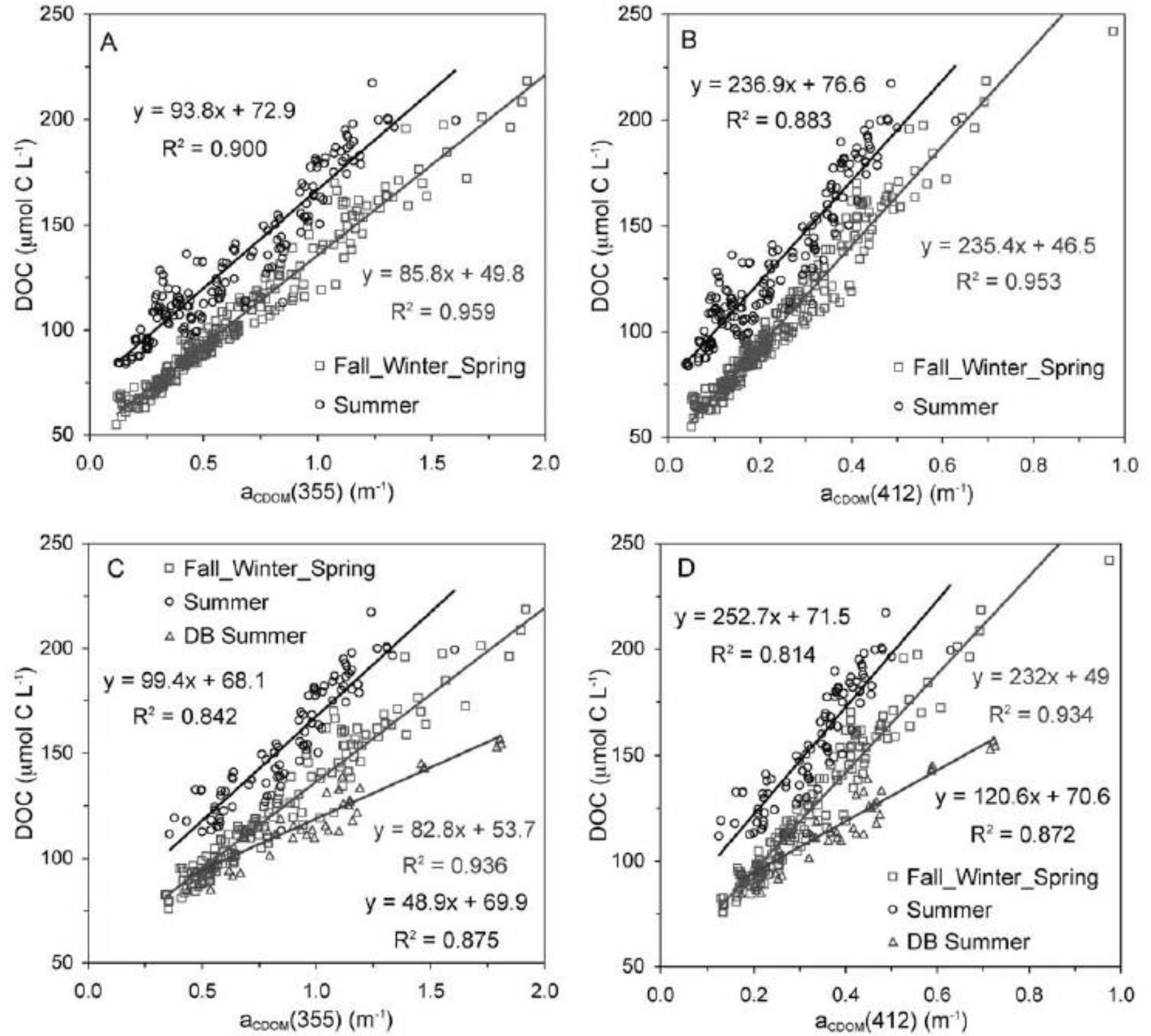
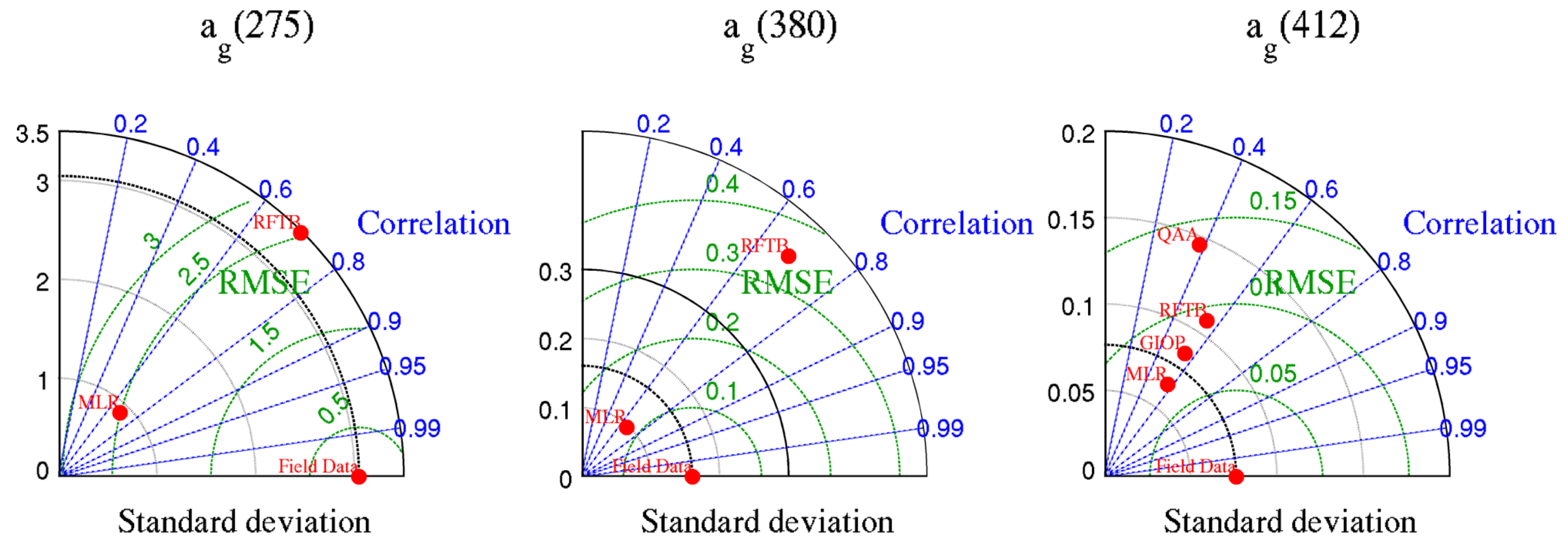
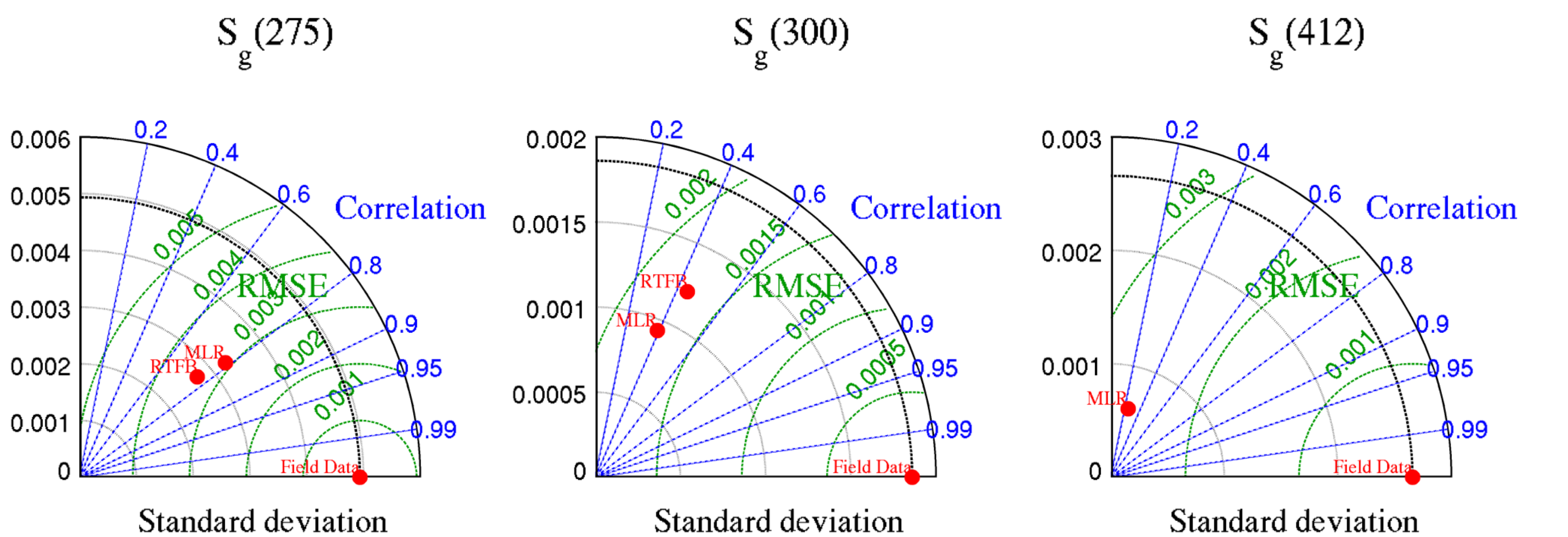


Figure 2. Seasonal relationships of dissolved organic carbon (DOC) and (A) $a_{CDOM}(355)$ (chromophoric dissolved organic matter absorption coefficient at 355 nm) or (B) $a_{CDOM}(412)$ within the MAB and between DOC and (C) $a_{CDOM}(355)$ or (D) $a_{CDOM}(412)$ in the Chesapeake Bay mouth and plume region for the 2004–2006 research cruises and Delaware Bay mouth and plume region for the summer 2005–2006 cruises (DB Summer). Data shown for Fall_Winter_Spring (October–May) include measurements from all depths sampled, but only the top 2 depths for the Chesapeake Bay mouth transect (depicted in Figure 1A). Summer (June–September) data only include the top 2 depths sampled (surface mixed layer) and exclude the Delaware Bay mouth and plume stations (open triangles in Figure 1).

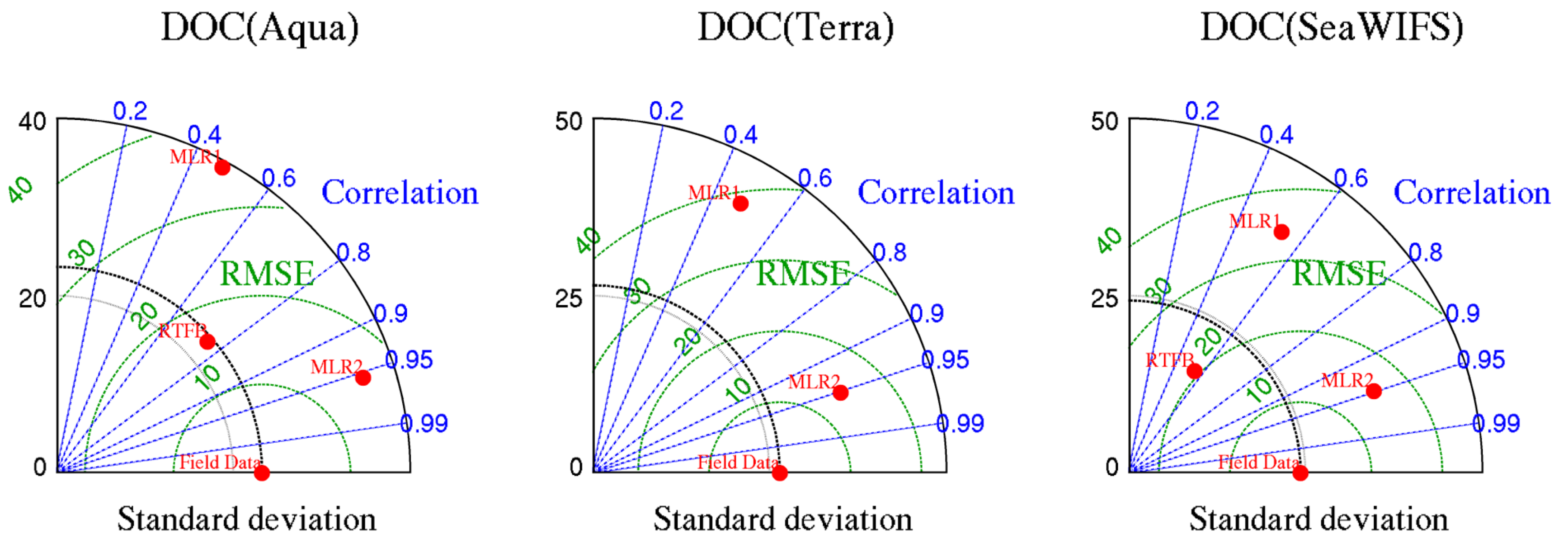
Algorithm Validation



a g (275)
a g (380)
a g (412)
Correlation
RMSE
Standard deviation
MLR
RFTB
QAA
GIOP
Field Data

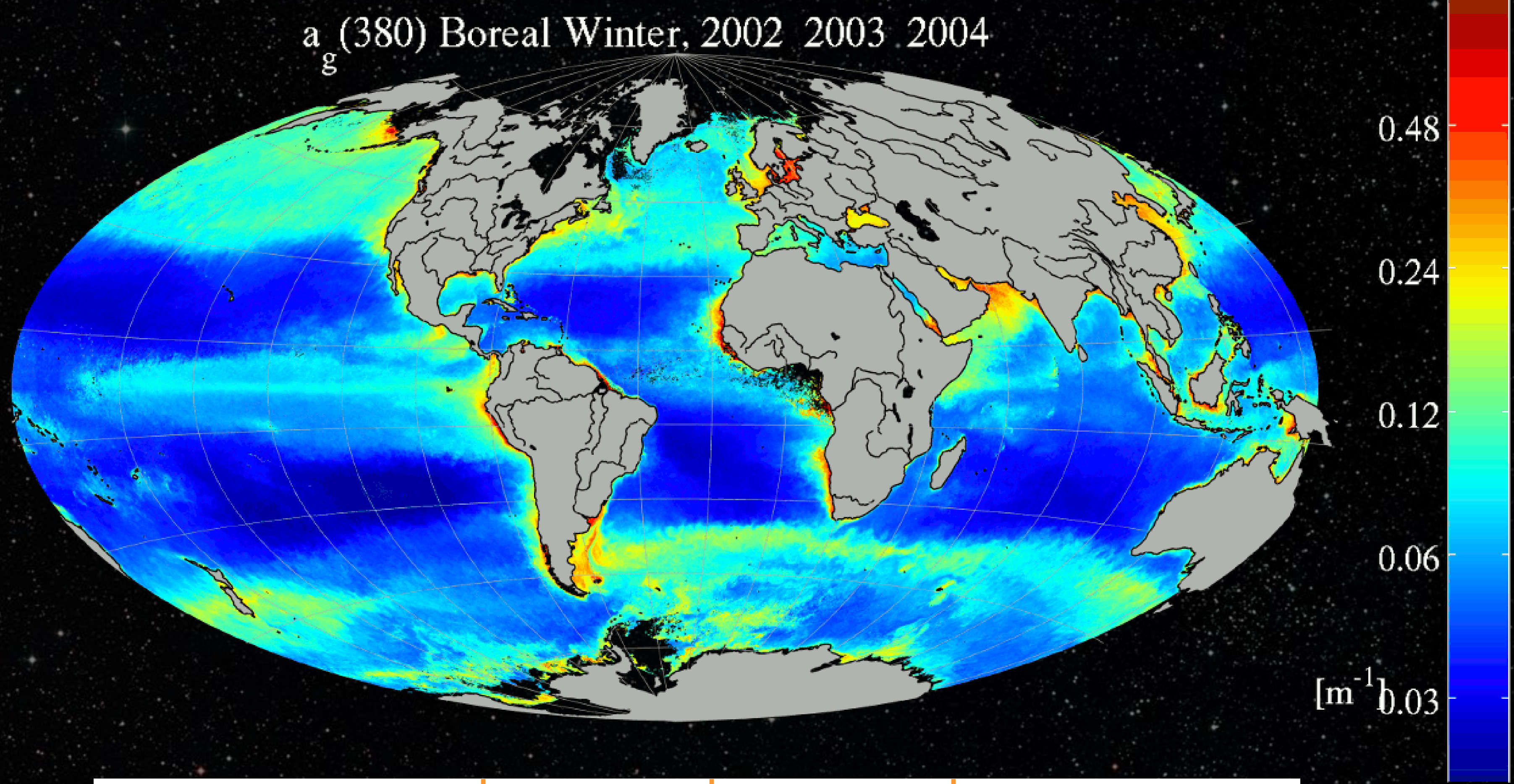


S g (275)
S g (300)
S g (412)
Correlation
RMSE
Standard deviation
MLR
RTFB
Field Data

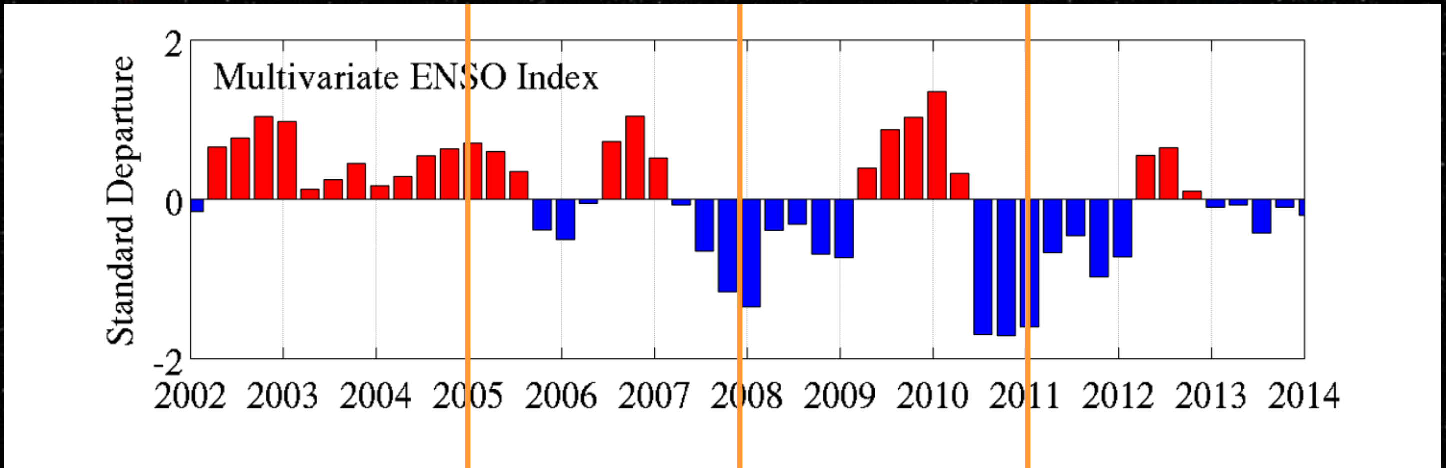


DOC(Aqua)
DOC(Terra)
DOC(SeaWIFS)
Correlation
RMSE
Standard deviation
MLR1
MLR2
RTFB
Field Data
0.2
0.4
0.6
0.8
0.9
0.95
0.99

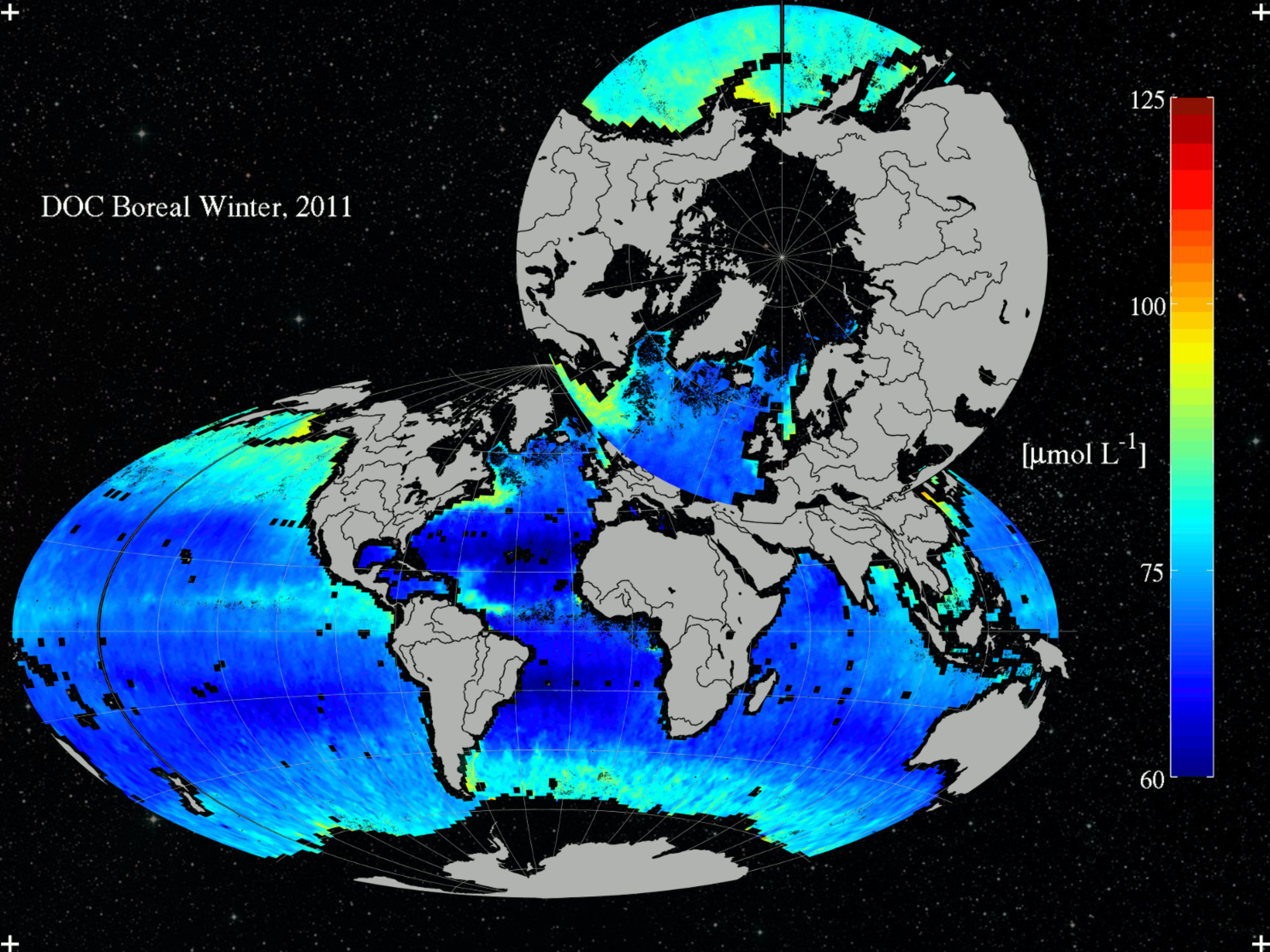
Algorithm Application

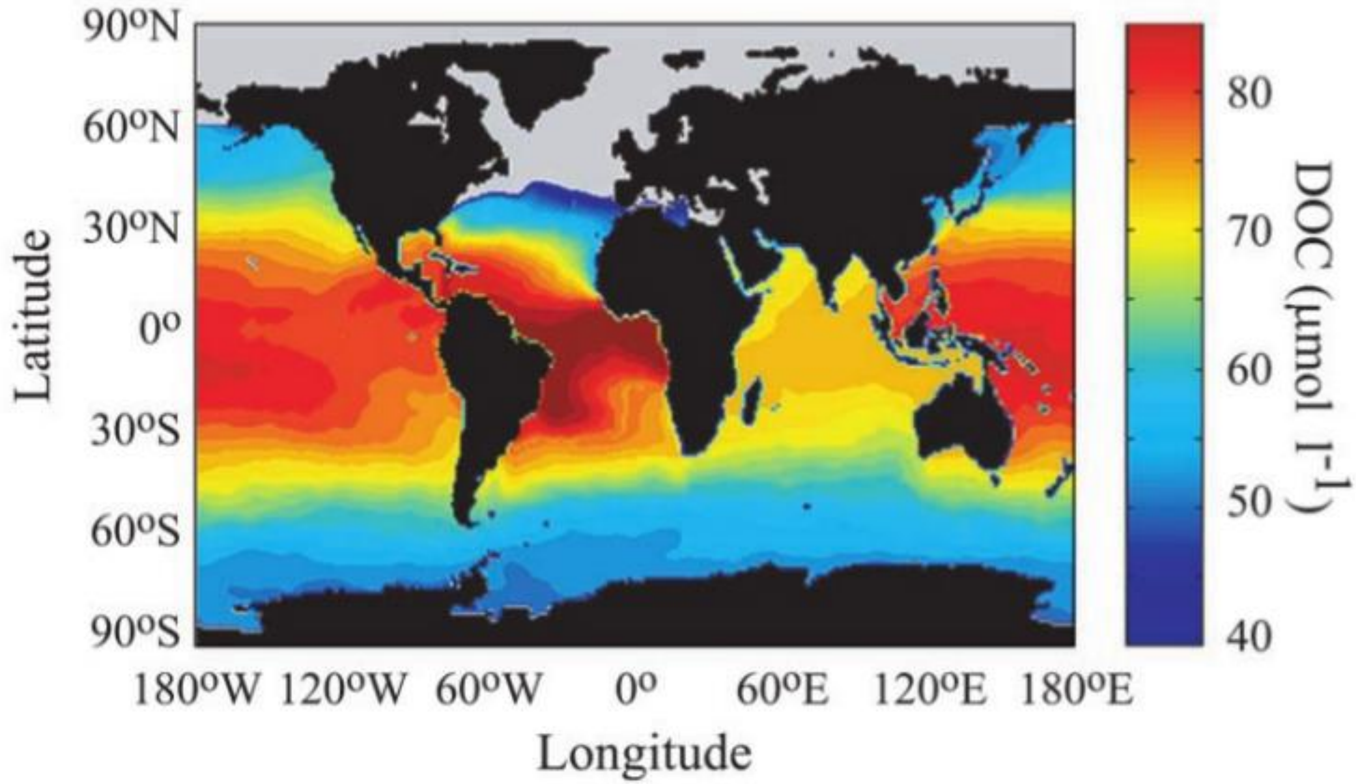


a_g(380) Boreal Winter, 2002 2003 2004
0.48
0.24
0.12
0.06
[m^-1] 0.03



Multivariate ENSO Index
Standard Departure
2
0
-2
2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014


DOC Boreal Winter, 2011
125
100
75
60
[µmol L-1]



JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 107, NO. C12, 3228, doi:10.1029/2001JC000965, 2002

Figure 9. Climatological DOC distribution from a regression analysis based upon wintertime SST values. Concentrations of DOC are in units of μmol L^{-1}. The regression models used are presented in Table 2, and further details may be found in the text.

Global distribution and dynamics of colored dissolved and detrital organic materials

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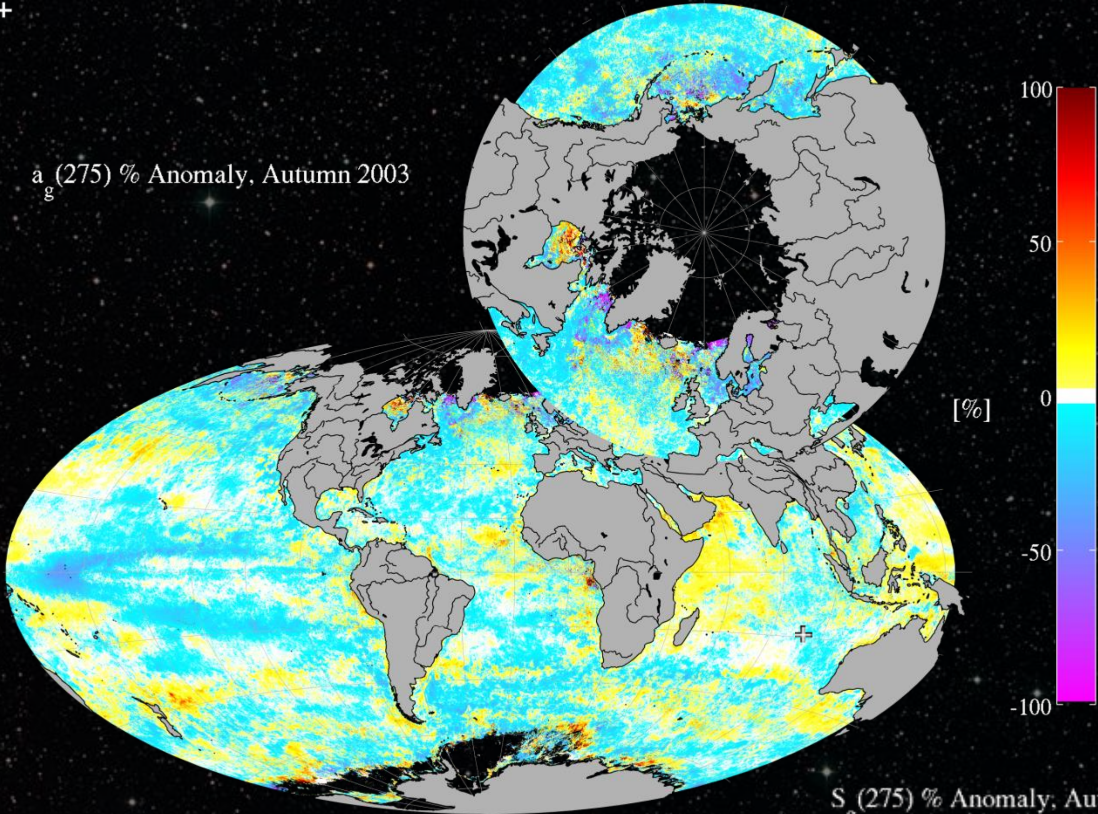
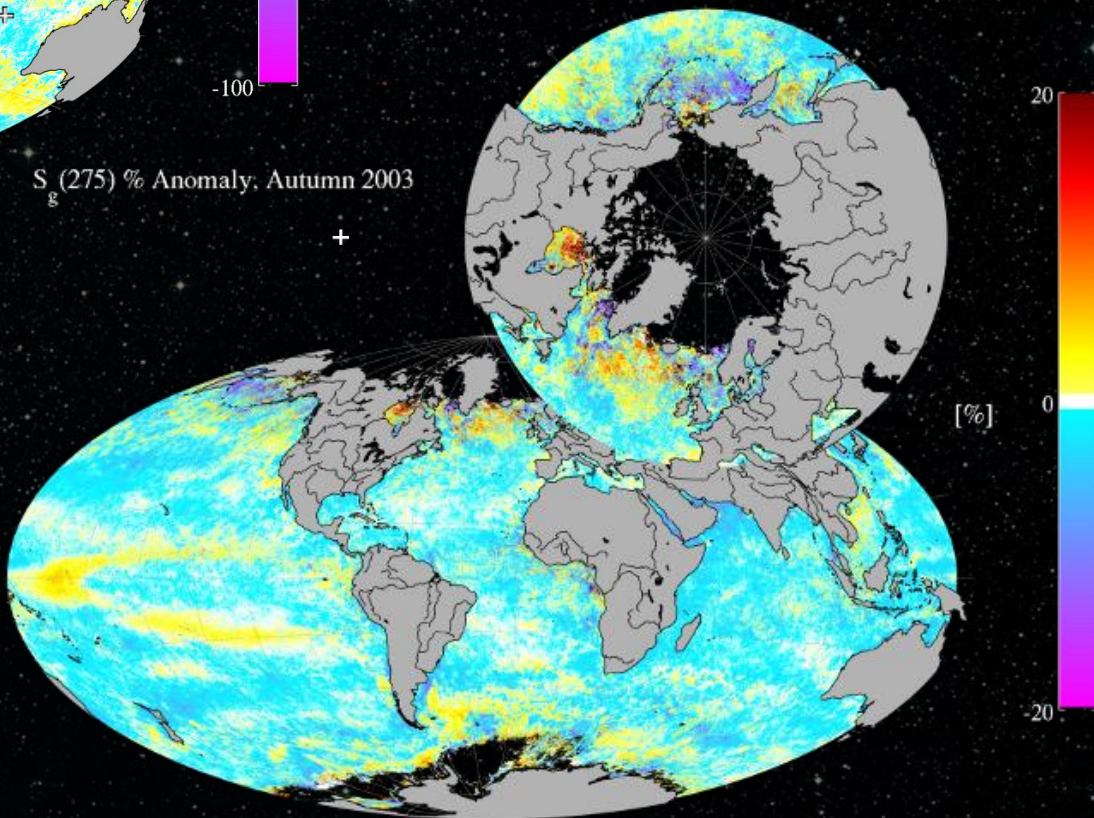
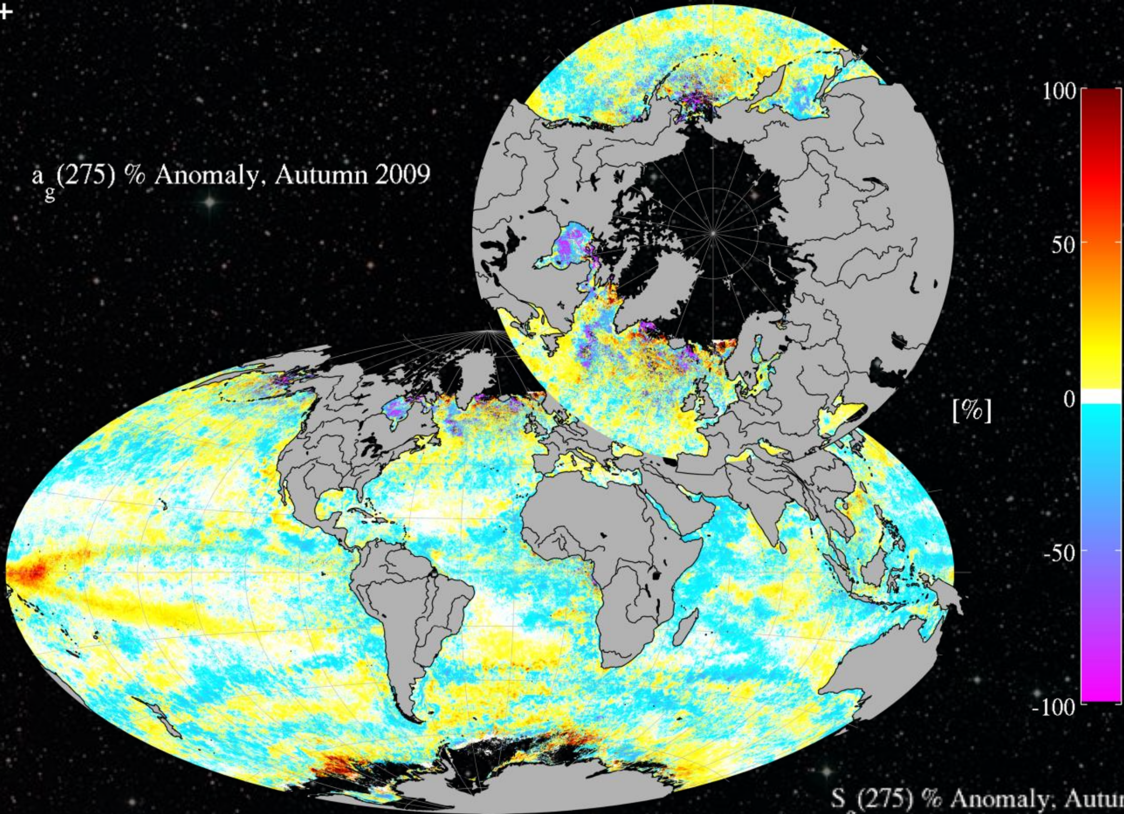
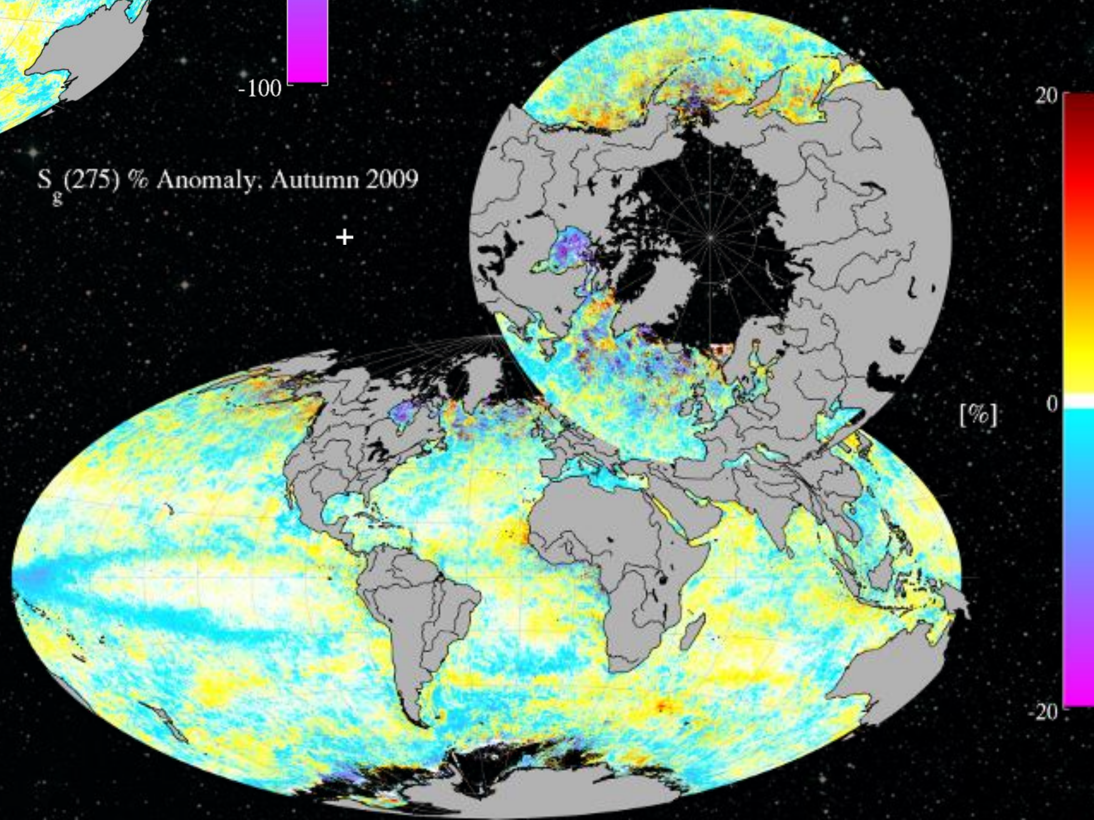


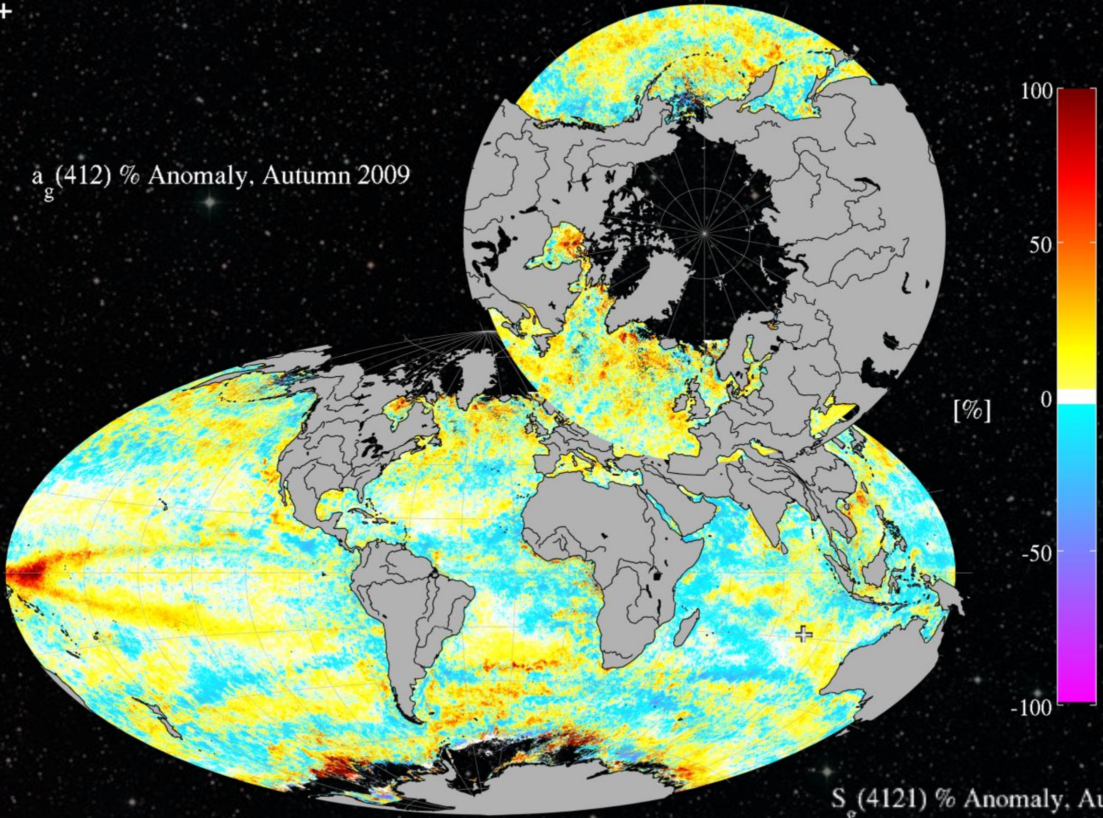


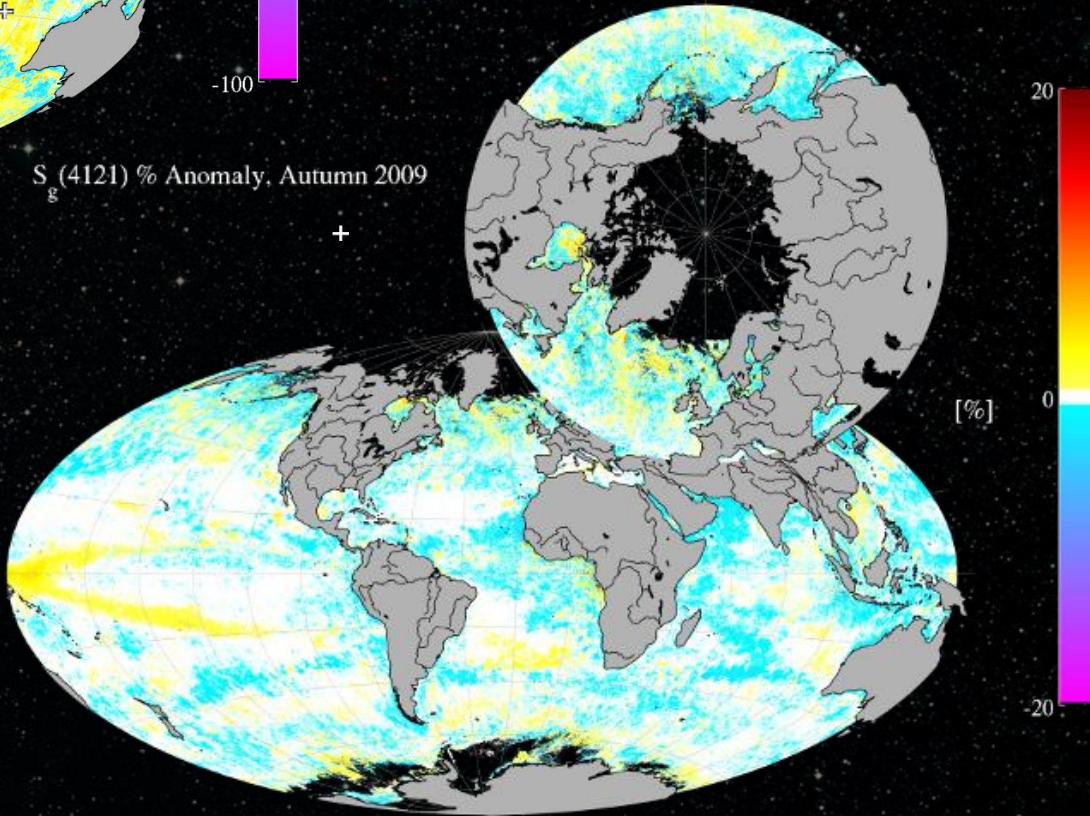
ANOMALY =
YEARBLOCK – AQUA-ERA-AVERAGE





ANOMALY =
YEARBLOCK – AQUA-ERA-AVERAGE





ANOMALY =
YEARBLOCK – AQUA-ERA-AVERAGE

Summary

Remote sensing of CDOM, spectral slope, and DOC are important to understanding marine carbon budgets and the underwater light field

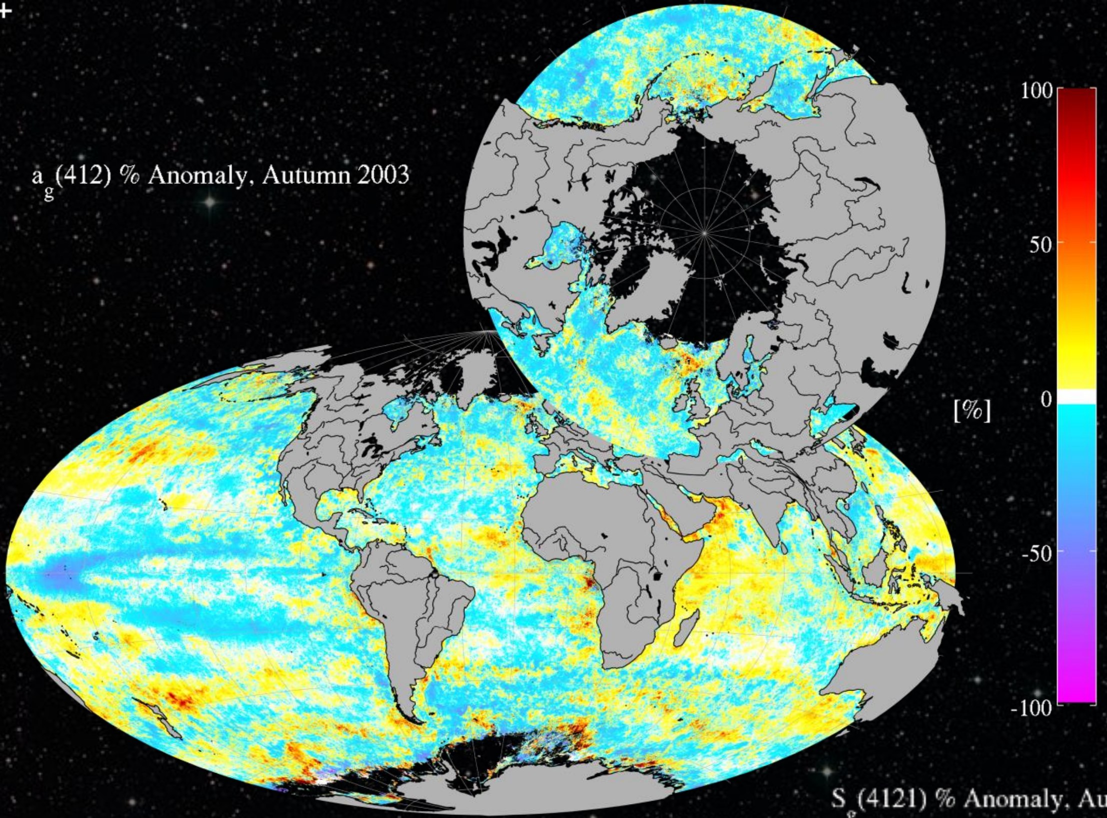
GOCAD is a global, carbon-centric, algorithm development database including hyperspectral data extending into the UV with ~50k field stations

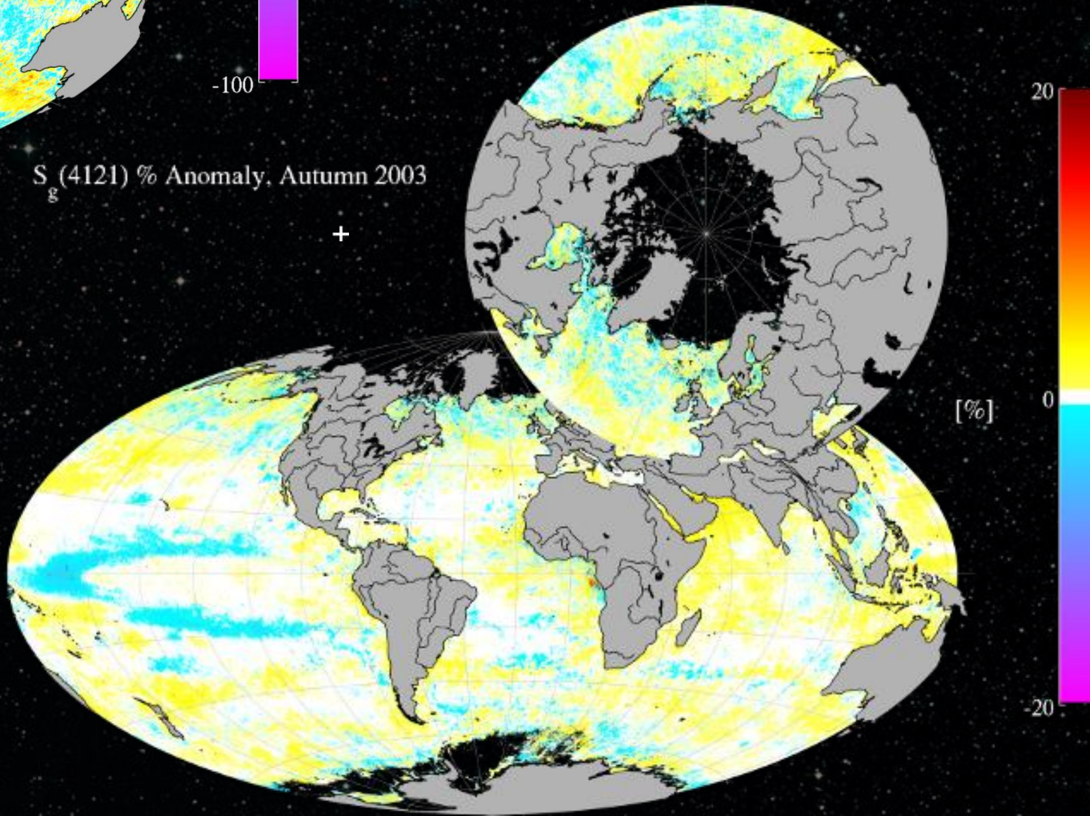
Several algorithms performed reasonably well retrieving $a_g(\lambda)$, $S_g(\lambda)$, and DOC, but MLR proved the most versatile and easy to implement on satellite imagery

- Combining ocean color imagery with SSS from Aquarius vastly improved retrievals of DOC

Aurin, Dirk A., Mannino, A., Larry, D., *Remote sensing of CDOM and dissolved organic carbon in the global ocean*, in prep.

EXTRA SLIDES





ANOMALY =
YEARBLOCK – AQUA-ERA-AVERAGE

CDOM

- Strongly absorbs in the blue and UV
  - Limits light for photosynthesis
  - Shades cells from UV damage
  - Leads to surface heating/stratification
- Together with chlorophyll, CDOM dominates the blue-green ratio of sea-surface reflectance
  - Increases uncertainty in band-ratio algorithms for Chl
  - S_g important to semi-analytical retrievals, particularly those that separate CDOM from non-algal particulate absorption

CDOM Remote Sensing

2001 Kahru et. alia (regional)

2002 D'Sa et al. (regional)

2003 Johannsen et al. (regional)

2008 Mannino et al. (regional)

2009 Morel & Gentili (CDOM *index*)

2011 Zhu et al. (regional)

2011 Tiwari et al. (NOMAD)

2011 Shanmugan et al. (NOMAD)

2011 Matthews (review)

2012 Odermatt (review)

2012 Brando et al. (regional)

2012 Tilstone et al. (regional)

2013 Doug et al. (regional,NOMAD)

2013 Tahrani et al. (regional)

2013 Swan et al. (CLIVAR, n=127)

2013 Matsuoka et al. (regional)

...